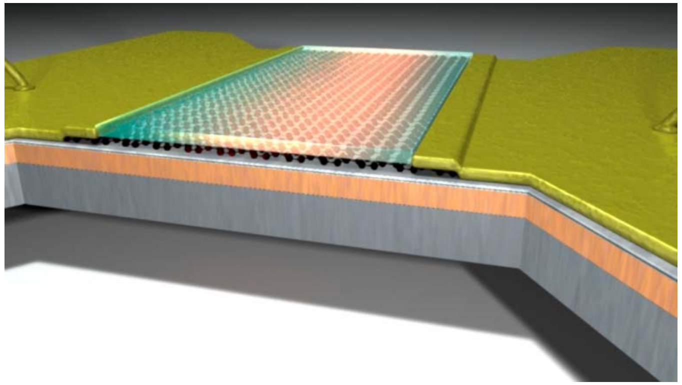
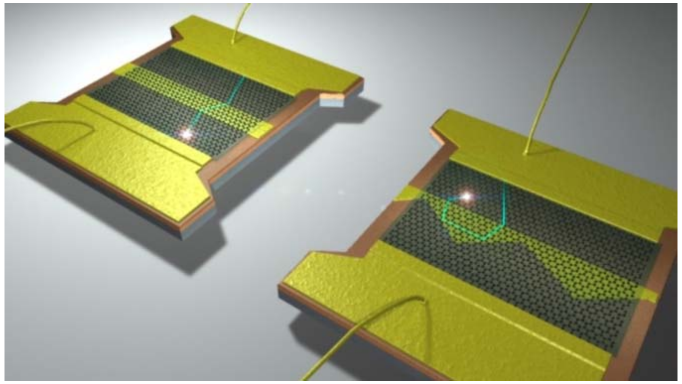
HF-Graphene Electronics





noise (L1)

(electron-phonon)

ballistic's (L2)

(Dirac Fermion Optics)

Bernard Plaçais

placais@lpa.ens.fr

Why studying noise ?

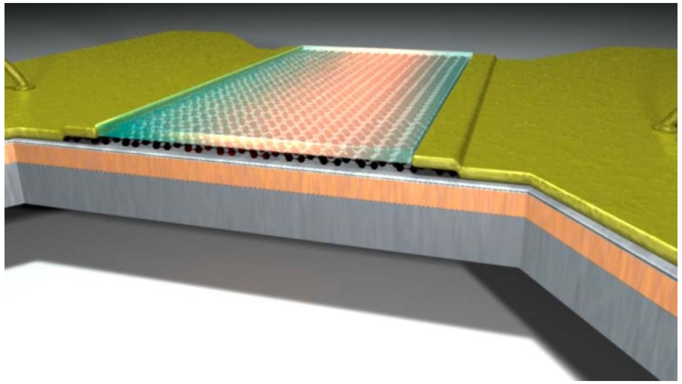
Because noise limits the performance of graphene electronics

Because it tells us something about graphene physics

It may be usefull to something

Finally, because it is there ….. « noise is the signal »

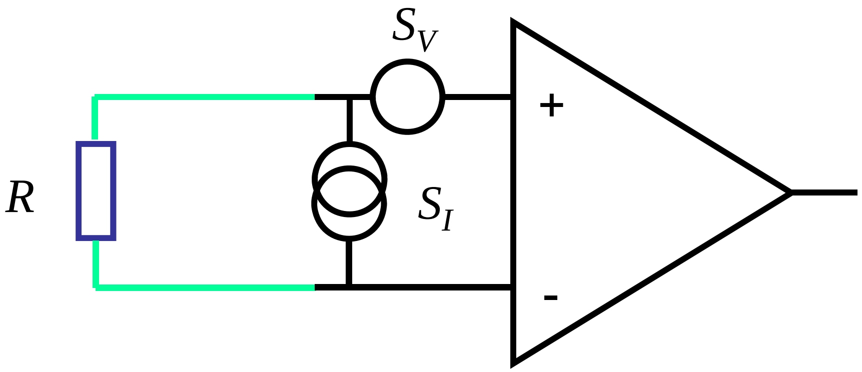
L1: Noise outline



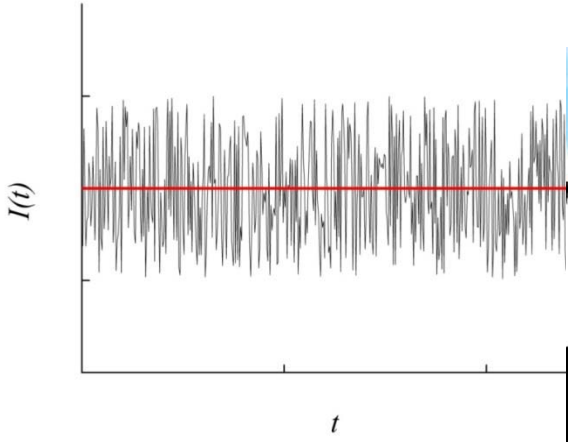
- Introduction noise physics
- Quantum shot noise in graphene
- Hot-electron noise in graphene
- Phonon cooling in graphene
- Perspectives

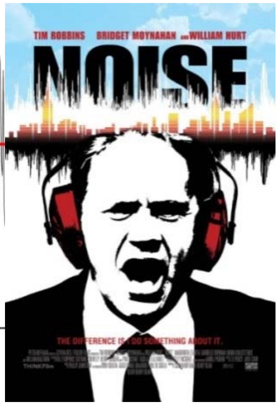
electrical noise

Noise of an amplifier



$$S_V^{in} = S_V + R^2 S_I$$

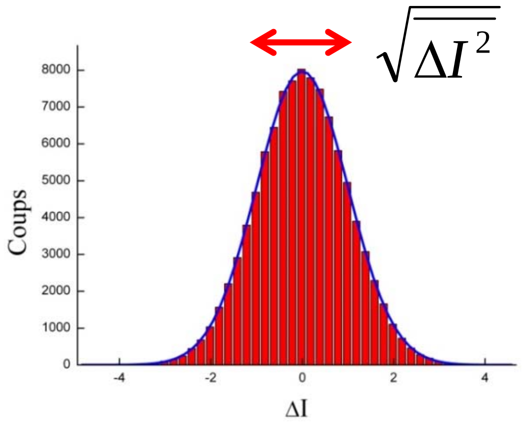




Statistical distribution

Fluctuations : $\Delta I(t) = I(t) - \overline{I(t)}$

Noise spectrum : $\overline{\Delta I^2(t)} = \boxed{\int S_I(\nu)} \Delta\nu$



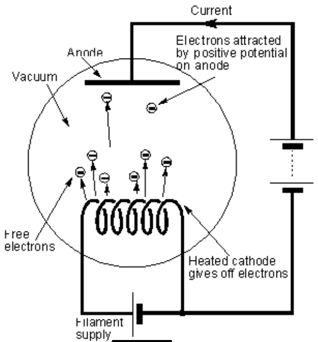
Basic noises in macro-systems

GRAPHENE FLAGSHIP

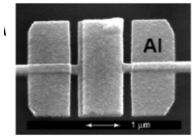
Shot-noise

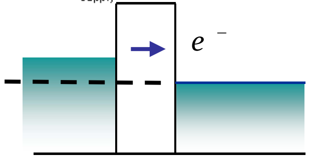
Equilibrium noise

Vacuum tube



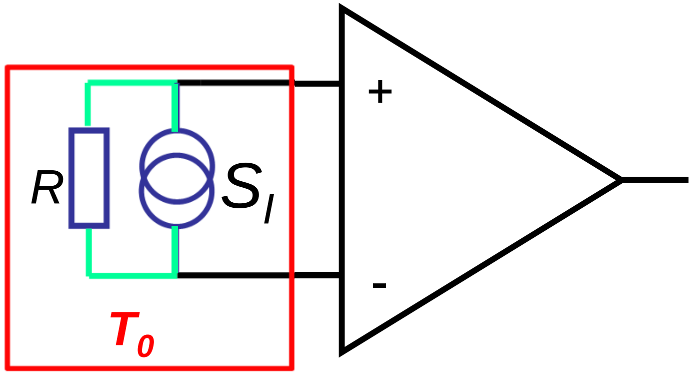
Tunnel junction





W. Schottky

$$S_I = 2e\bar{I}$$

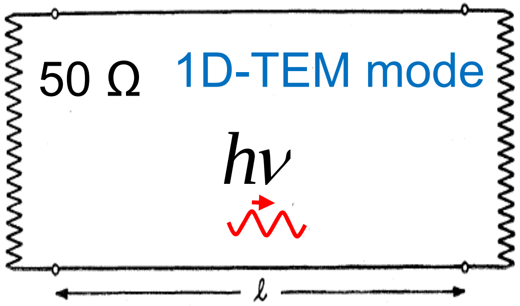


J.B. Johnson

$$S_I = 4\,k_B T_0 / R$$

Noise in macro-systems

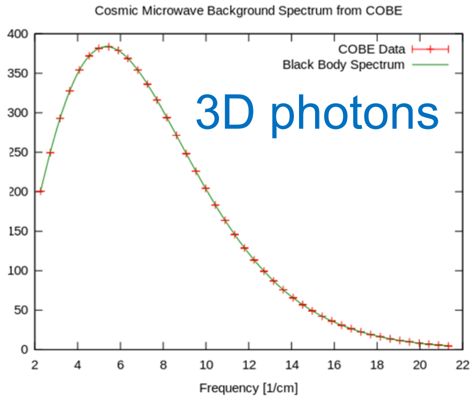
RF-black-body



H. Nyquist

$$\boxed{P_{RF} = S_{IV}/4 = k_B T_o}$$

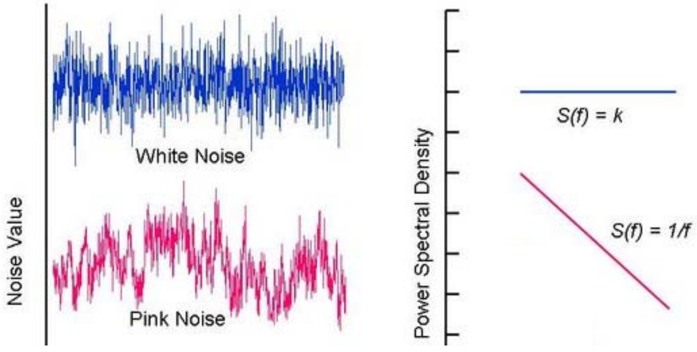
Optical black-body



M. Planck

$$\boxed{P_{Planck} = \frac{2hf^3}{c^2}\frac{1}{e^{hf/kT} - 1}}$$

Resistance noise



J. Hooge

$$\boxed{S_R/R^2 = \frac{\alpha_H}{N_c f}}$$

$$\alpha_H \sim 10^{-3}$$

coherent scattering shot noise

Conductance is transmission

$$G = 4\frac{e^2}{h}\sum_{1}^{N} T_n$$

Quantum scattering is noisy

$$S_I = 2eI\,\frac{\sum T_n\,(1 - T_n)}{\sum T_n} = 2eI \times \text{"}Fano\text{"}$$

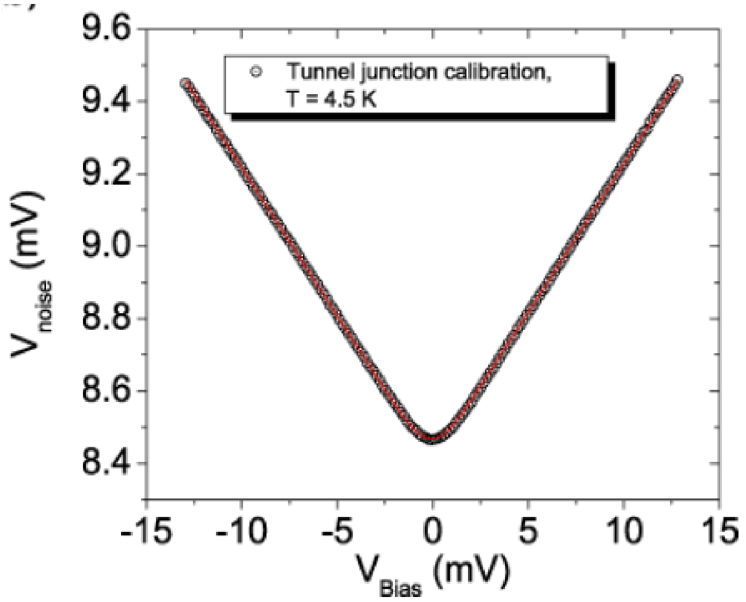
R. Landauer and M . Büttiker

Fano factor F<1 : a measure of noise intensity

Ya.M. Blanter, M. Büttiker / Physics Reports 336 (2000) 1-166

Combining population + scattering noise

$$S_I = 2\frac{e^2}{h}\left[2k_B\theta\sum T_n{}^2 + eV\coth\frac{eV}{2k_B\theta}\sum T_n\left(1-T_n\right)\right]$$



tunnel junctions are used as a primary noise standard

Thermal noise

$$S_I = 2\frac{e^2}{h}\left[2k_B\theta_o\sum T_n\right]$$
$$= 4Gk_B\theta_o$$

Tunnel junction

$$S_I = 2\frac{e^2}{h}\left[eV\sum T_n\right]$$
$$= 2eI$$

Diffusive metal

$$S_I = 2eI \times \frac{1}{3}$$

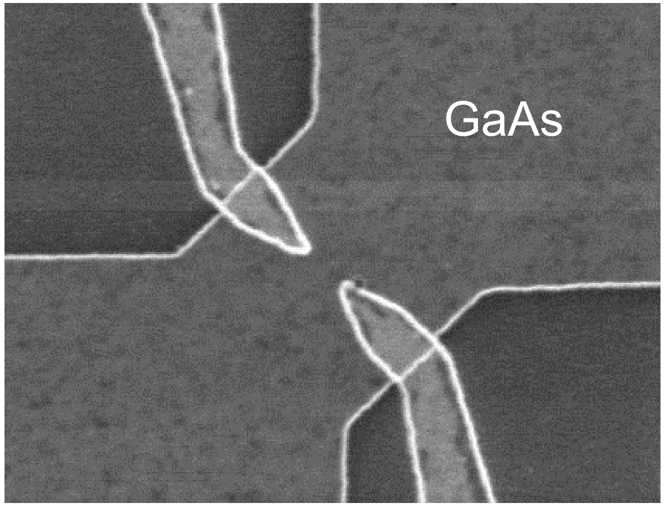
Q-point contact

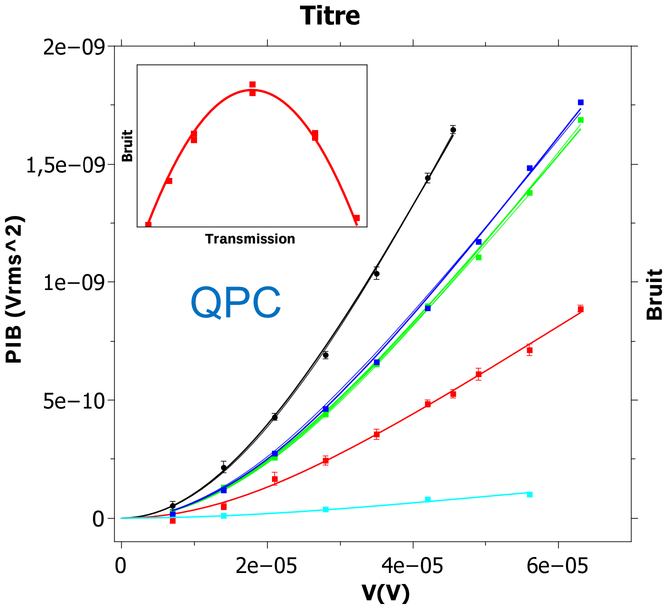
$$S_I = 2\frac{e^2}{h}\left[eVT(1-T)\right]$$
$$= 2eI(1-T)$$

Combining population + scattering noise

$$S_I = 2\frac{e^2}{h}\left[2k_B\theta\sum {T_n}^2 + eV\coth\frac{eV}{2k_B\theta}\sum T_n\left(1-T_n\right)\right]$$

soon
QPC in Graphene
(CNRS-Grenoble)





Thermal noise

$$S_I = 2\frac{e^2}{h}\left[2k_B\theta_o\sum T_n\right]$$
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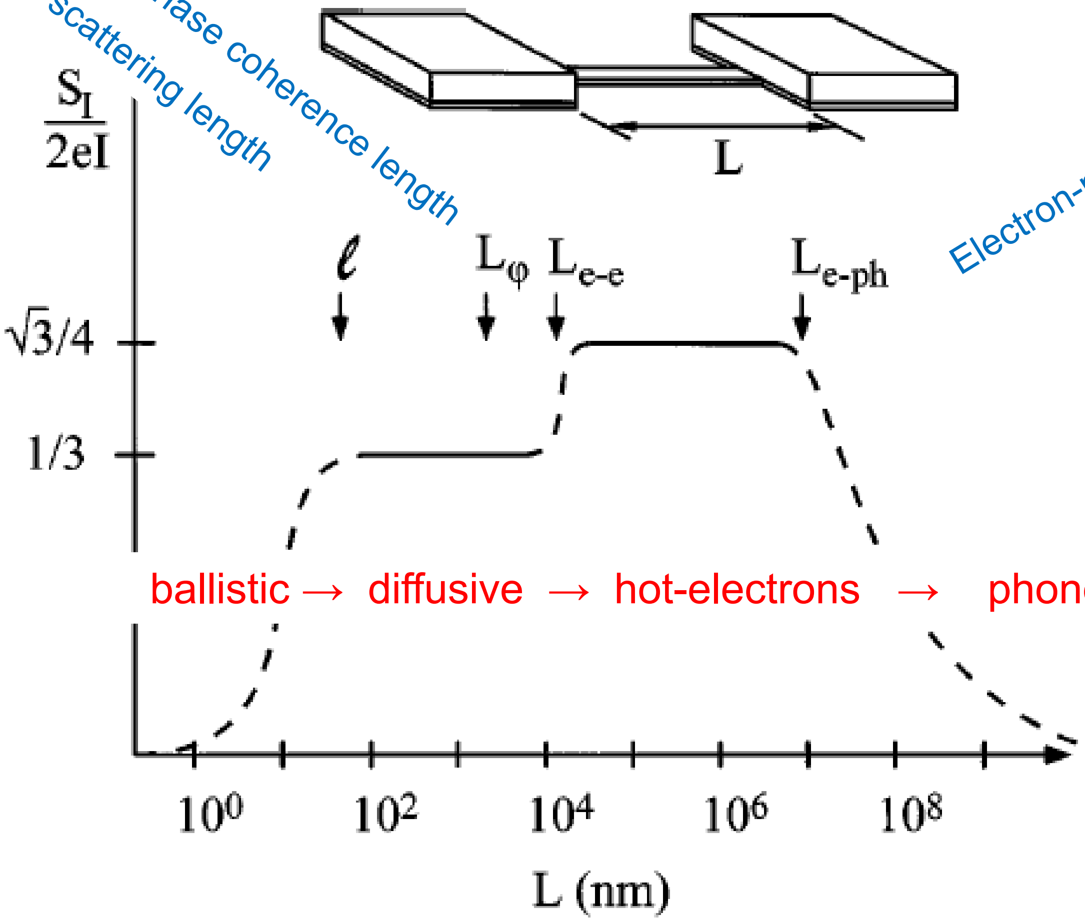
Metallic sample : from meso to macro

… on increasing the sample length



scattering length

phase coherence length

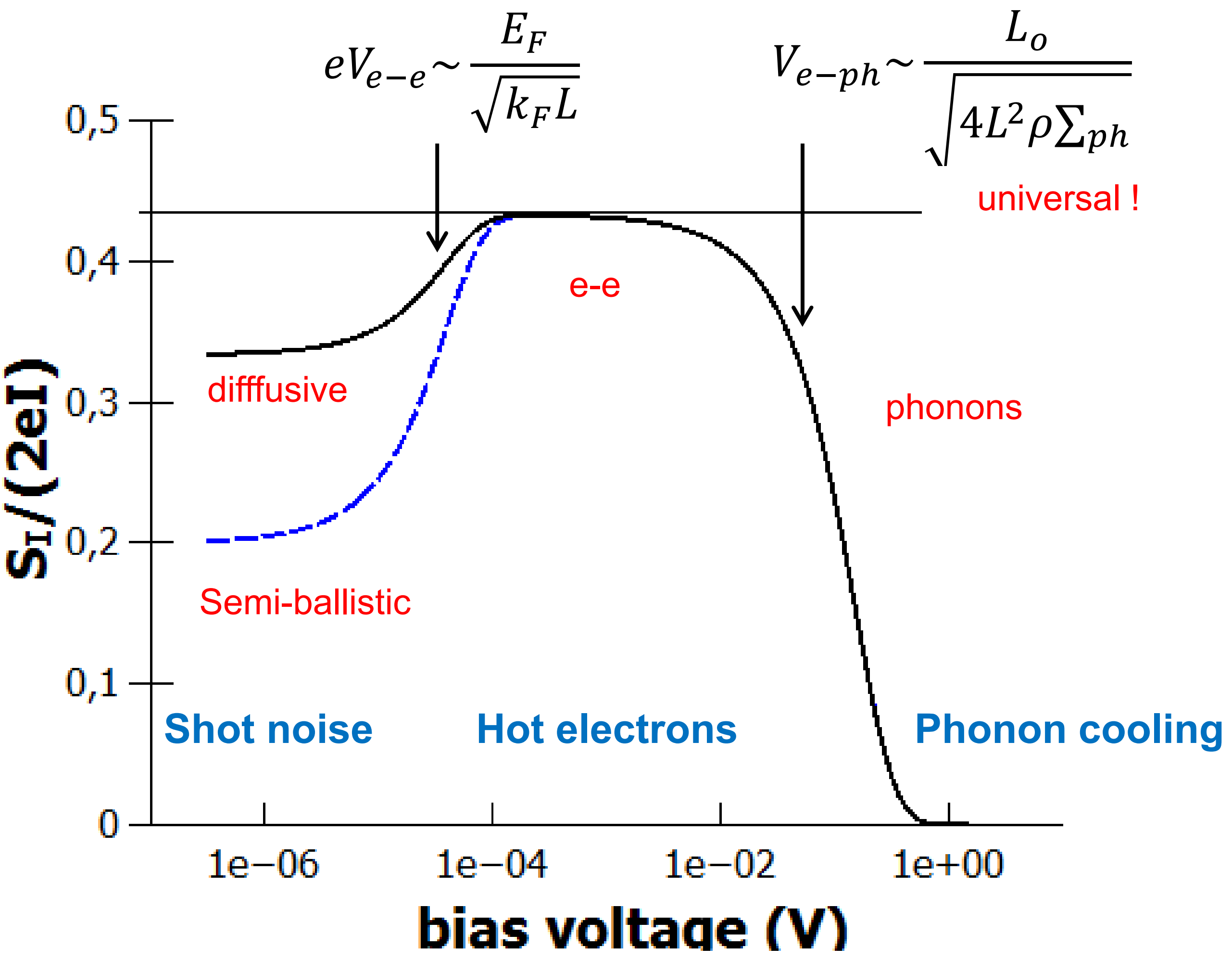
Electron-phonon length

ballistic → diffusive → hot-electrons → phonons → macroscopic world

A.H. Steinbach et al. / Phys. Rev. Lett. 76(1996) 3806

Metallic sample : from meso to macro

… on increasing the bias voltage



$$eV_{e-e} \sim \frac{E_F}{\sqrt{k_F L}}$$

$$V_{e-ph} \sim \frac{L_o}{\sqrt{4L^2 \rho \Sigma_{ph}}}$$

universal !

Current noise spectrum

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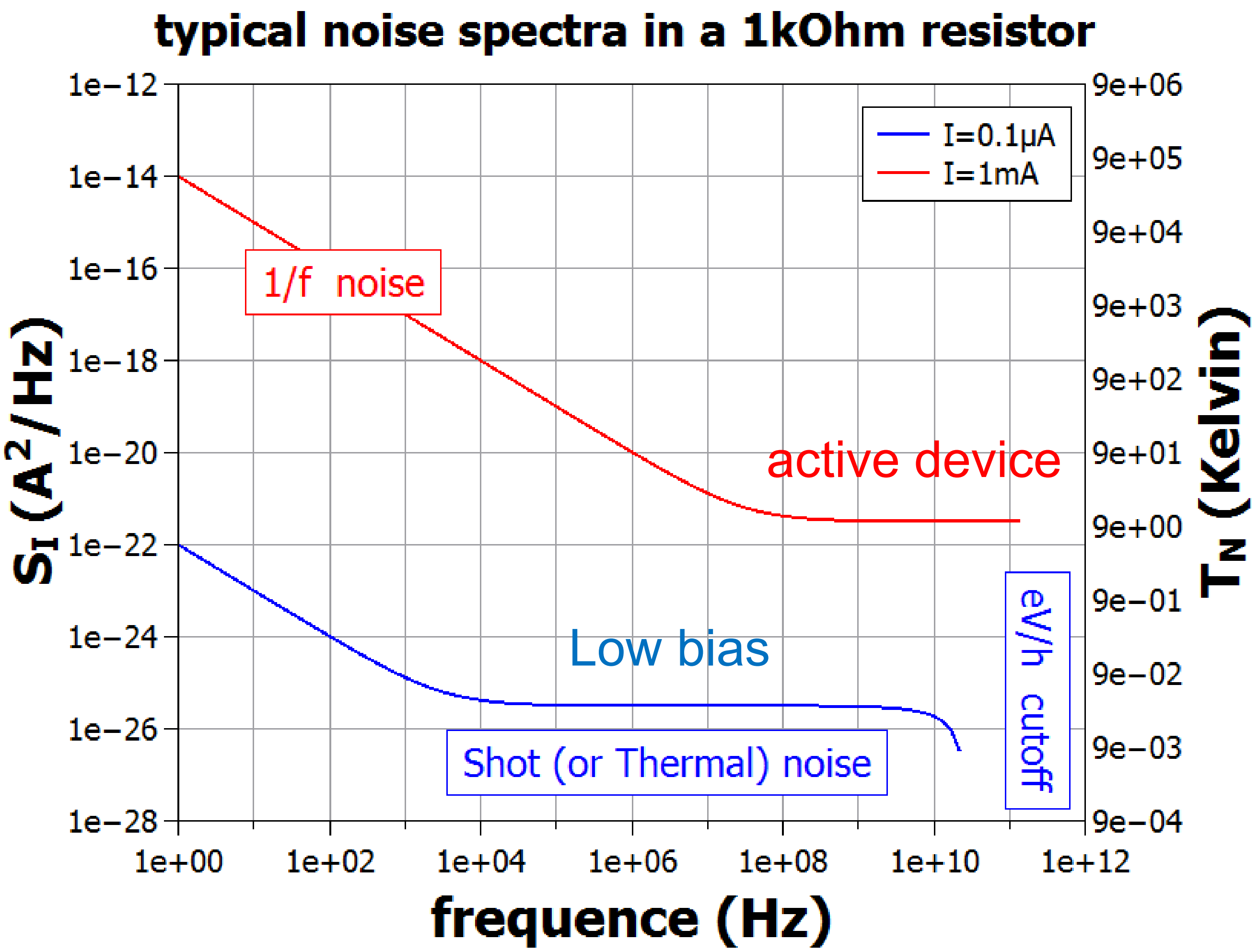
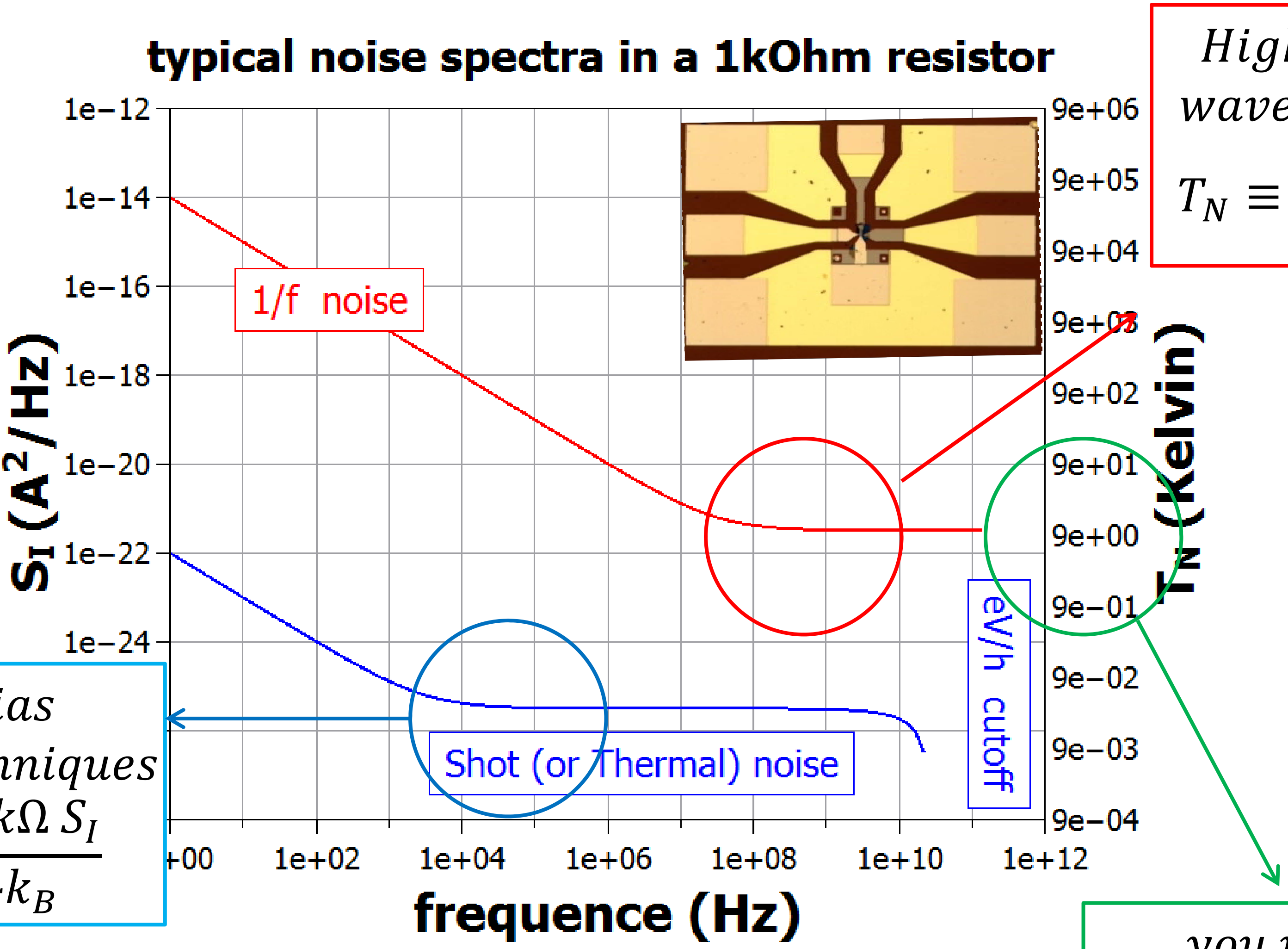


Current noise spectrum



High bias wave guide

$$T_N \equiv \frac{50\Omega\, S_I}{4k_B}$$

Low bias lockin techniques

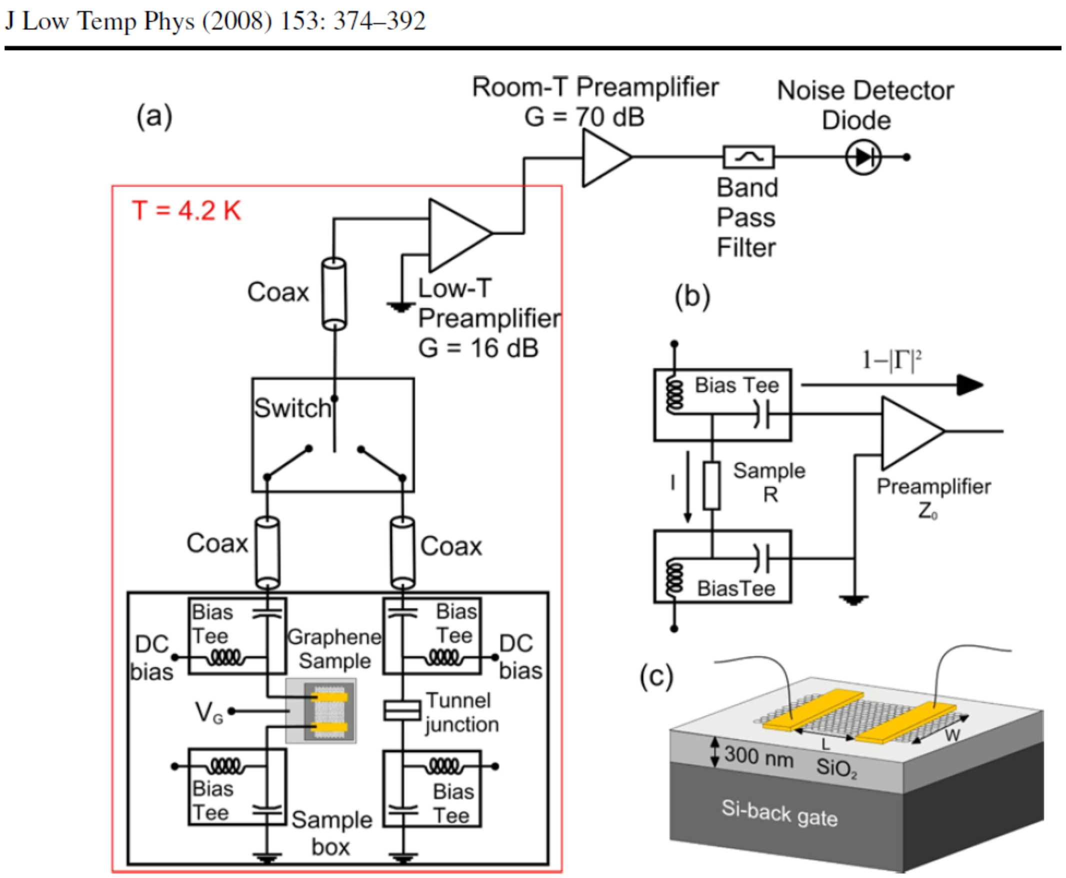
$$T_N = \frac{10k\Omega\, S_I}{4k_B}$$

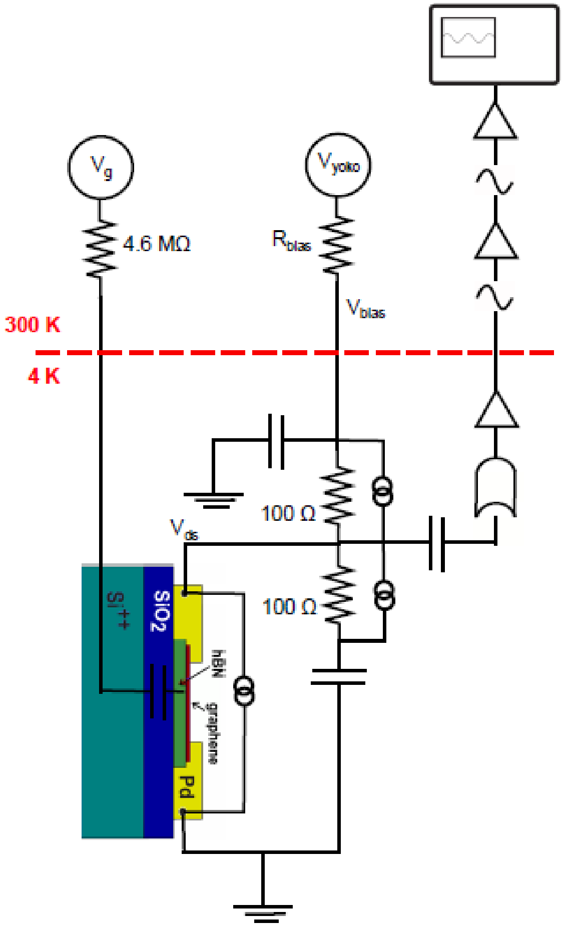
you need cryogenic LNAs !

Cryogenic RF-noise measurement

Aalto set-up (650-750 MHz)

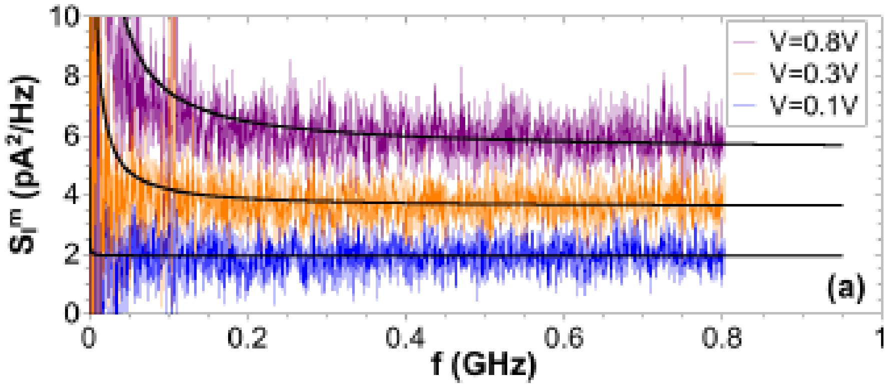
ENS-setup (0.1-2GHz, 1-12GHz)

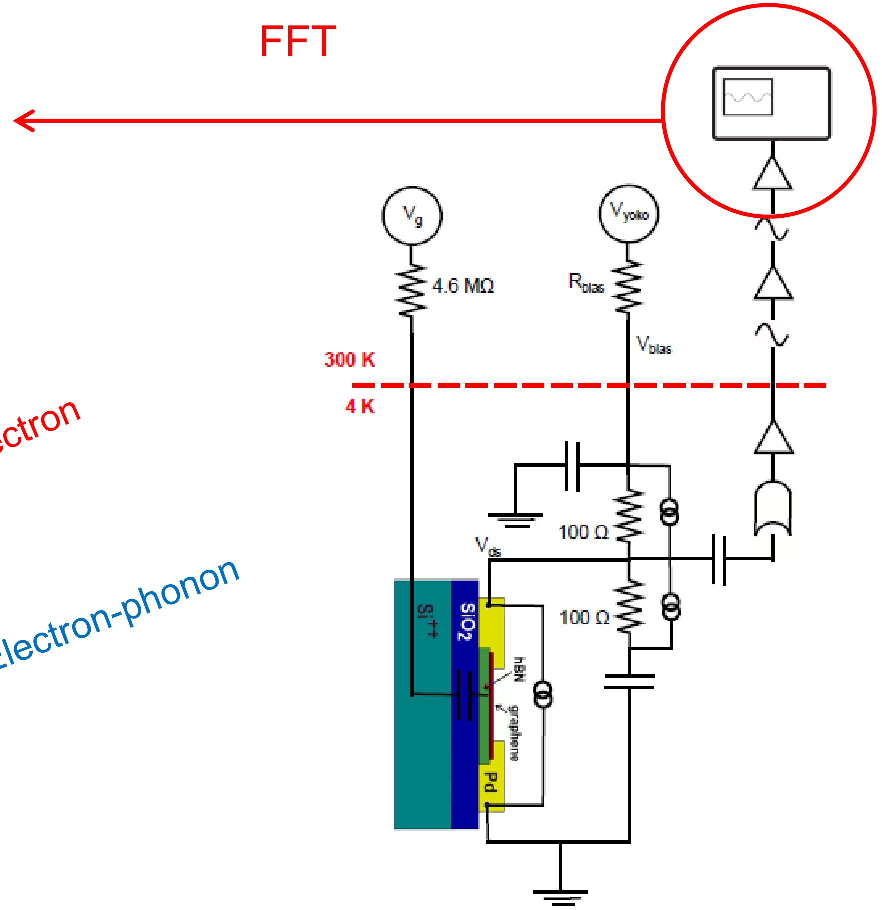

J Low Temp Phys (2008) 153: 374–392



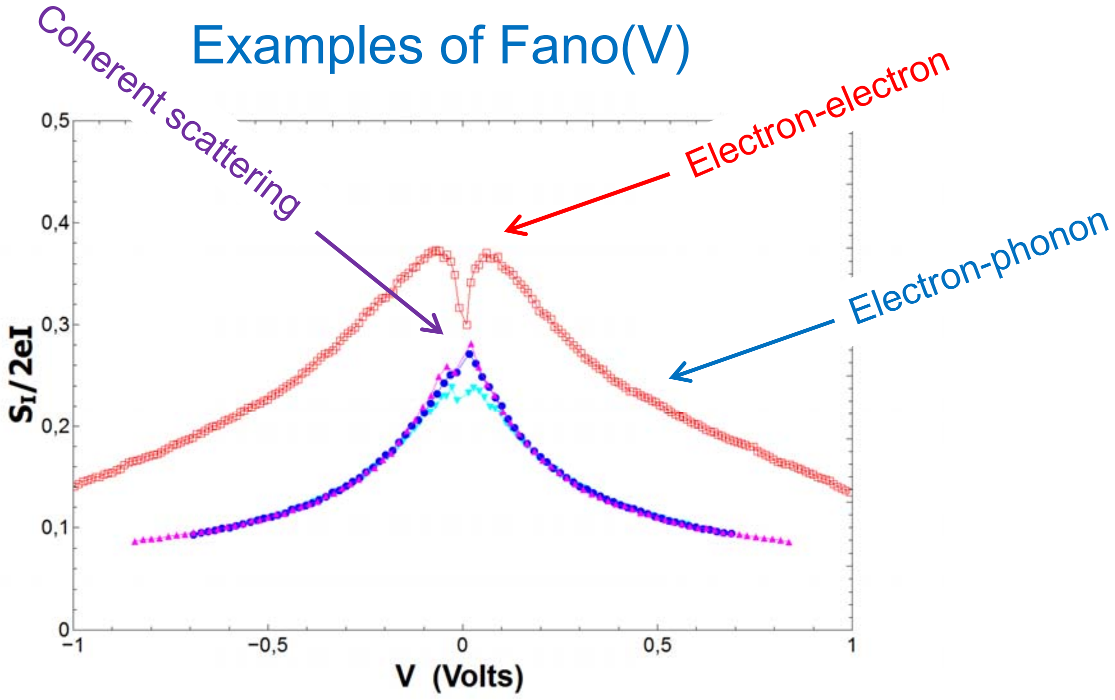
See : Antti Laitinen poster !!

Example of noise spectra and Fano factor plot





Examples of Fano(V)



A. Betz, PhD-thesis, https://tel.archives-ouvertes.fr/tel-00784346

L1: Noise in graphene devices

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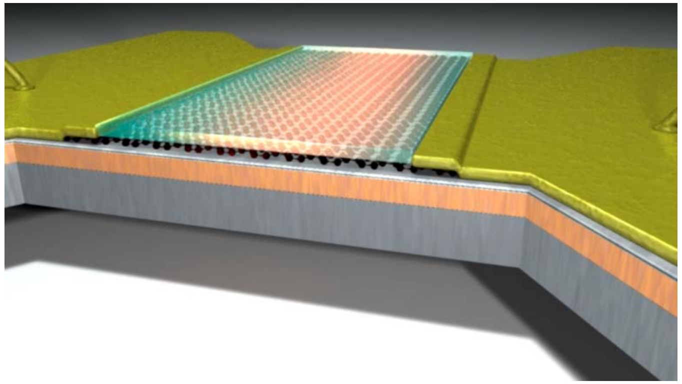

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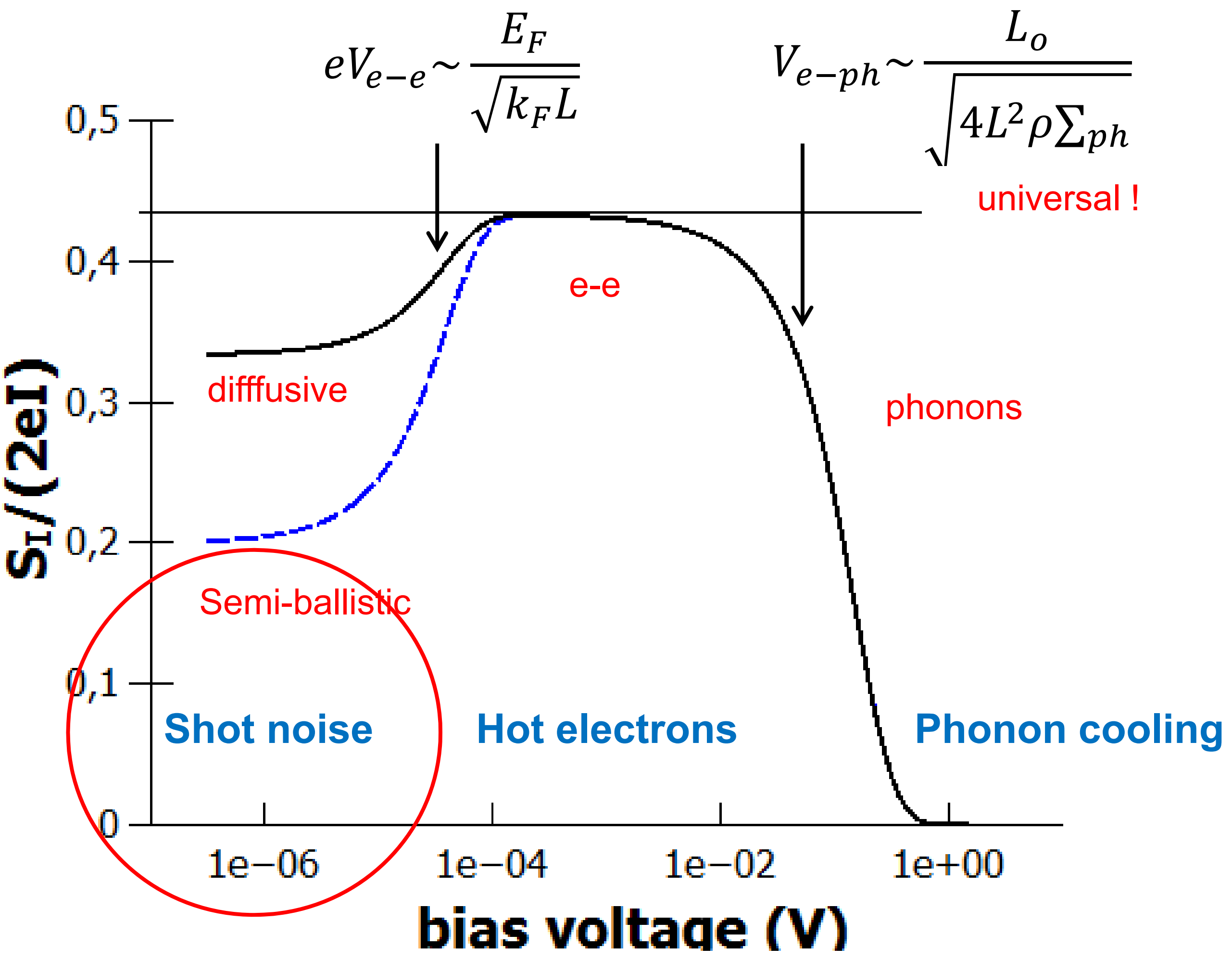
Metallic sample : from meso to macro

… on increasing the bias voltage



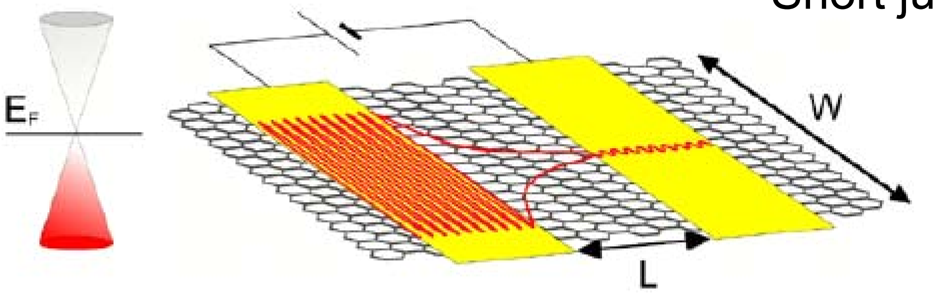
$$eV_{e-e} \sim \frac{E_F}{\sqrt{k_F L}}$$

$$V_{e-ph} \sim \frac{L_o}{\sqrt{4L^2 \rho \Sigma_{ph}}}$$

universal !

Shot noise in graphene junctions (@ DP)

Short junction with W>>L



Evanescent wave transmission
$$T_n^{Dirac} = \frac{1}{\cosh^2(\pi(n+\alpha)\frac{L}{W})}.$$

Conductance
$$\sigma_{Dirac} = G_{Dirac}\frac{L}{W} = \frac{4e^2}{h}\frac{L}{W}\int_0^\infty \frac{dk_y}{\cosh^2(k_y L)} = \frac{4e^2}{\pi h},$$

Fano
$$\mathcal{F}_{Dirac} = \frac{\sum_{n=0}^{N-1} T_n^{Dirac}(1-T_n^{Dirac})}{\sum_{n=0}^{N-1} T_n^{Dirac}} \equiv \frac{\int_0^\infty \frac{dk_y}{\cosh^2(k_y L)}(1-\frac{1}{\cosh^2(k_y L)})}{\int_0^\infty \frac{dk_y}{\cosh^2(k_y L)}} = \frac{1}{3}.$$

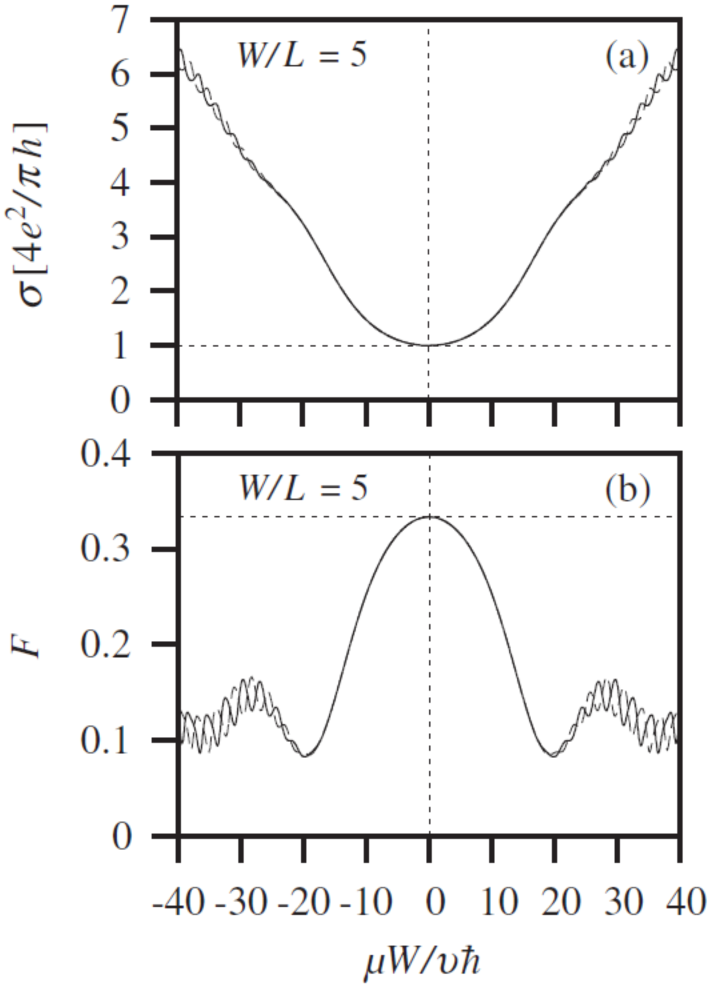
J. Tworzillo et al. / Phys. Rev. Lett. 96 (2006) 246802

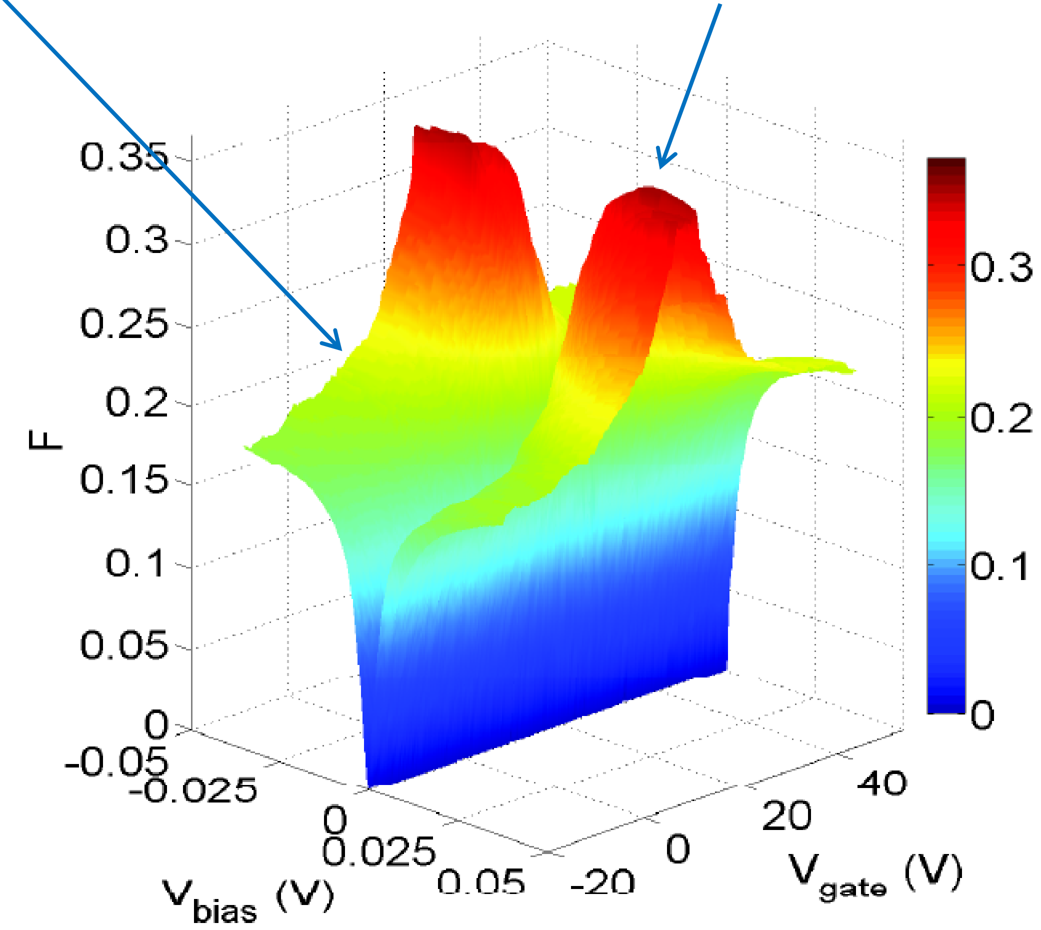
Shot noise in graphene junctions

GRAPHENE FLAGSHIP

Noise suppression in ballistic graphene (W=5L)

F=1/3 at DP





J. Tworzillo et al. / Phys. Rev. Lett. 96 (2006) 246802

R. Danneau et al./ Phys. Rev. Lett. 100 (2008) 196802

Shot noise in graphene ribbons

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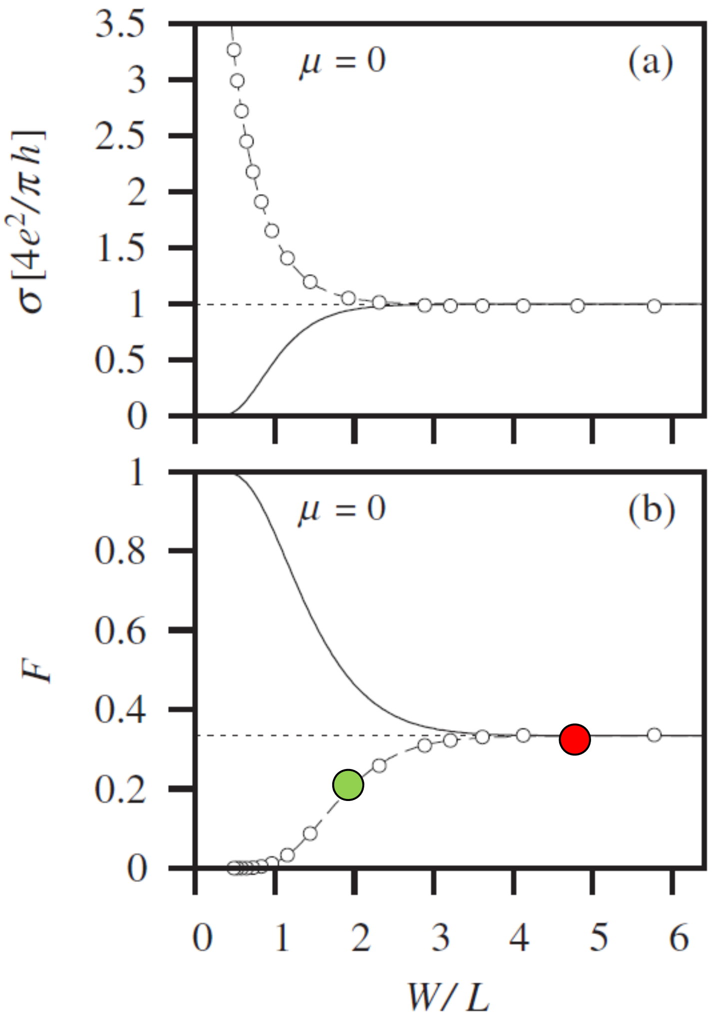
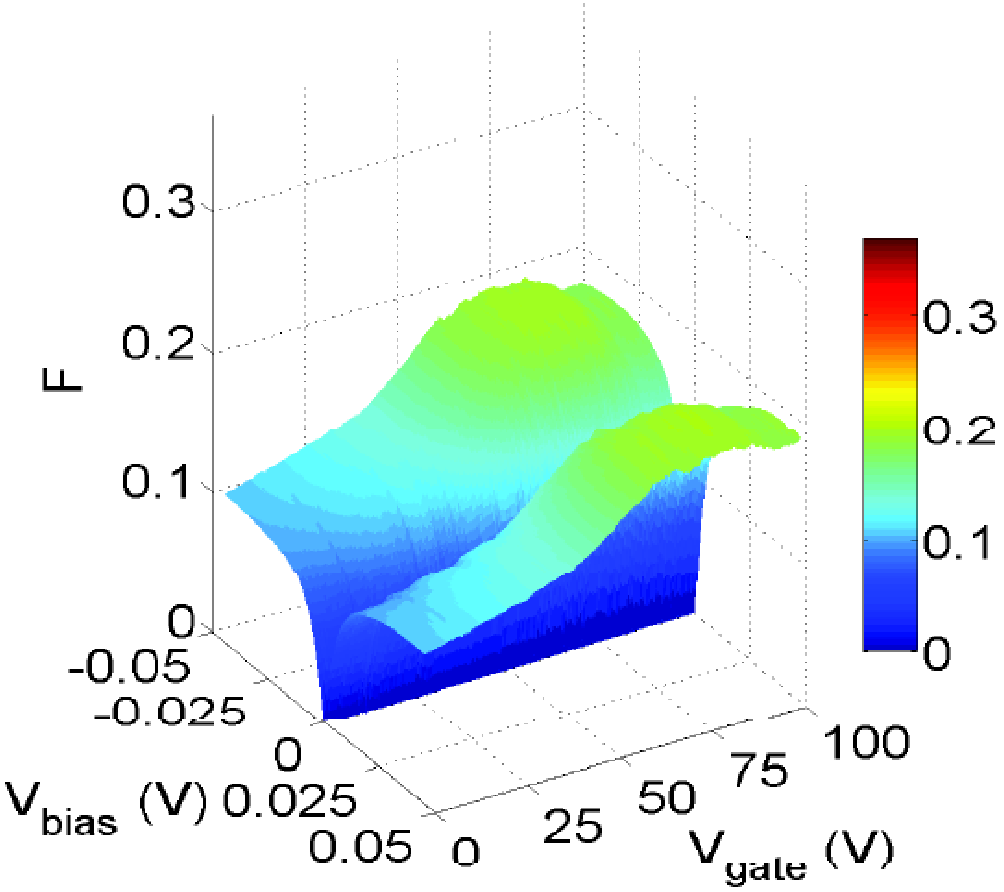
theory



experiment



J. Tworzillo et al. / Phys. Rev. Lett. 96 (2006) 246802

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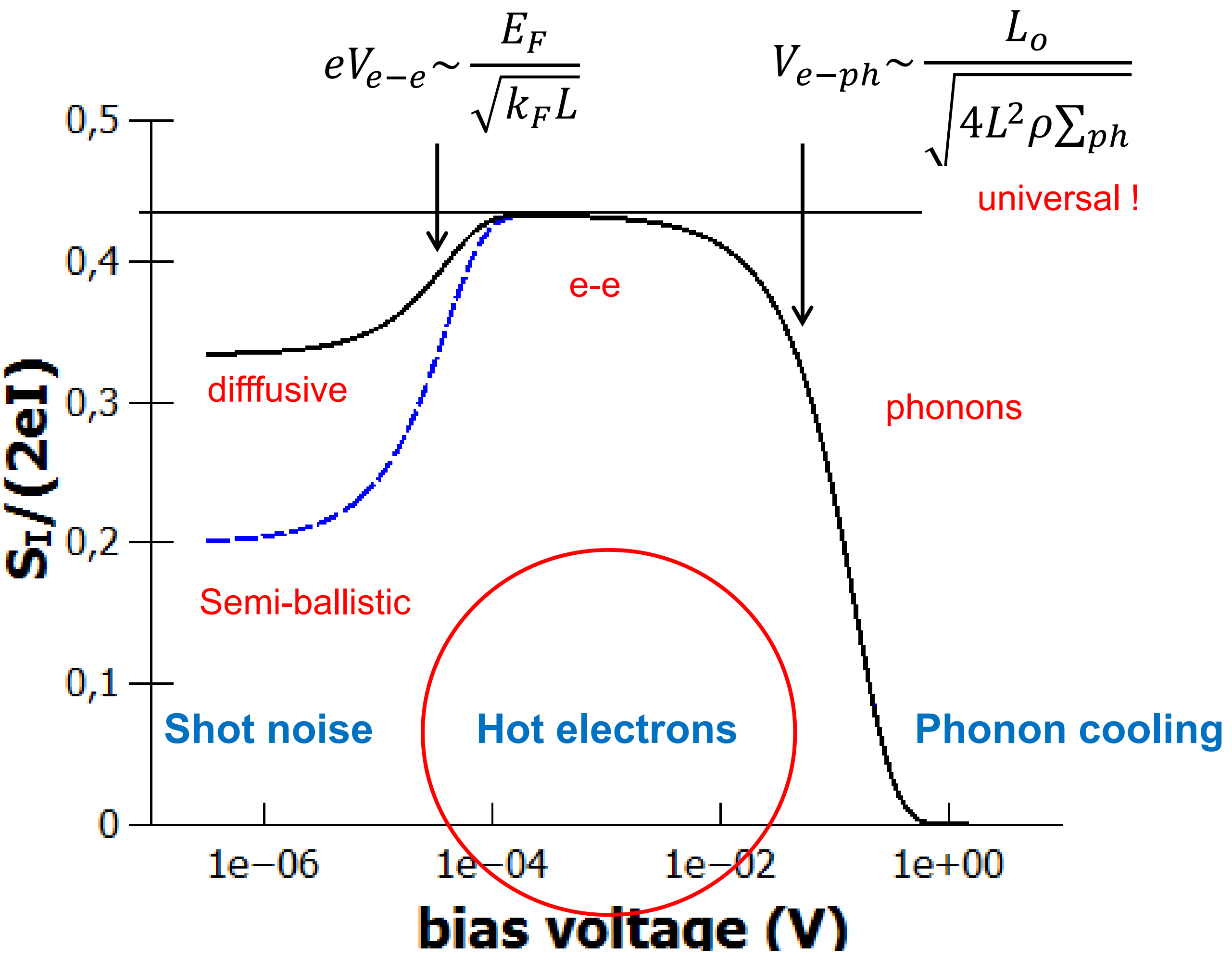
Metallic sample : from meso to macro

… on increasing the bias voltage



$$eV_{e-e} \sim \frac{E_F}{\sqrt{k_F L}}$$

$$V_{e-ph} \sim \frac{L_o}{\sqrt{4L^2 \rho \Sigma_{ph}}}$$

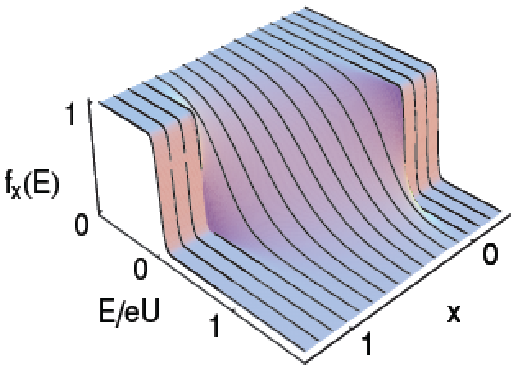
universal !

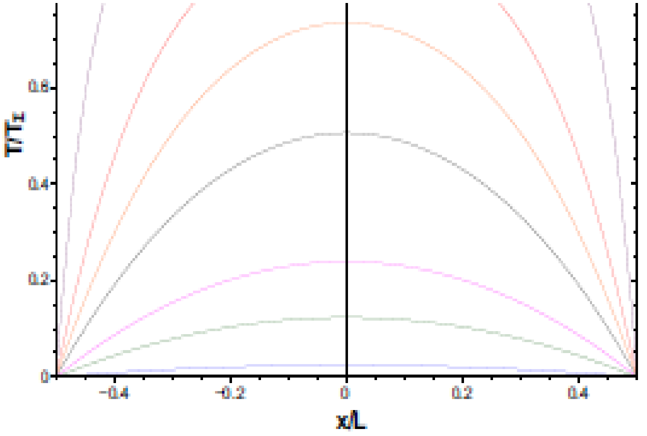
« Wiedemann-Franz regime »

GRAPHENE FLAGSHIP

e-e interactions at finite bias

=> µ(x) and electron temperature profile $T_e(x)$





$$f(\varepsilon, x) = \left[1 + \exp\left(\frac{\varepsilon - e\varphi(x)}{k_B T_e(x)}\right)\right]^{-1}$$

Heat equation : $\frac{T\partial\sigma}{\partial t} + div\,\boldsymbol{J_Q} = -\boldsymbol{J}.\boldsymbol{E}$

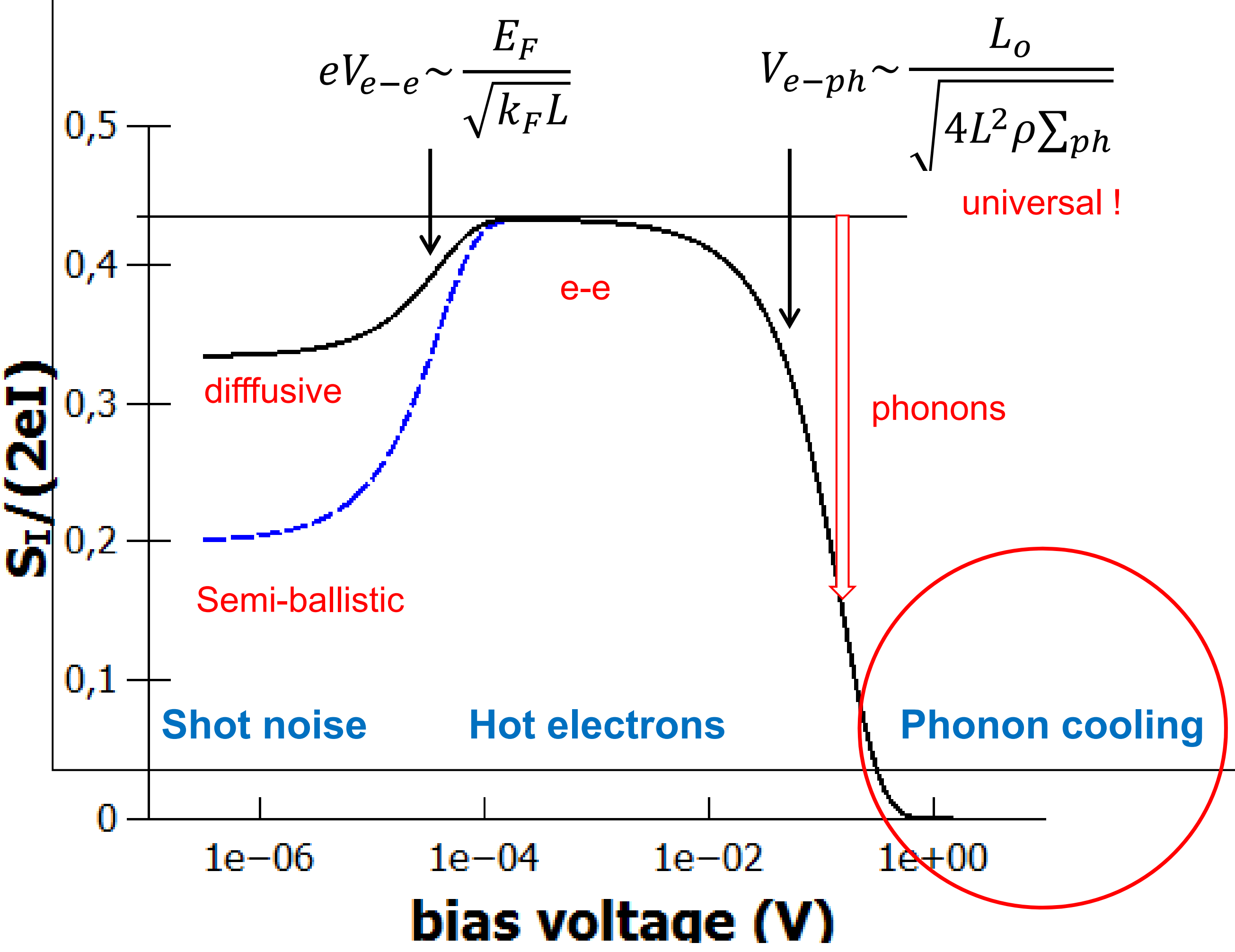
$$\frac{L_o}{2R}\frac{L^2\partial^2 T^2(x)}{\partial x^2} = -\frac{V^2}{R} \qquad with \quad L_o = \pi^2 {k_B}^2/3e^2 = 25\,nW\Omega K^{-2}$$

Hot electron shot noise

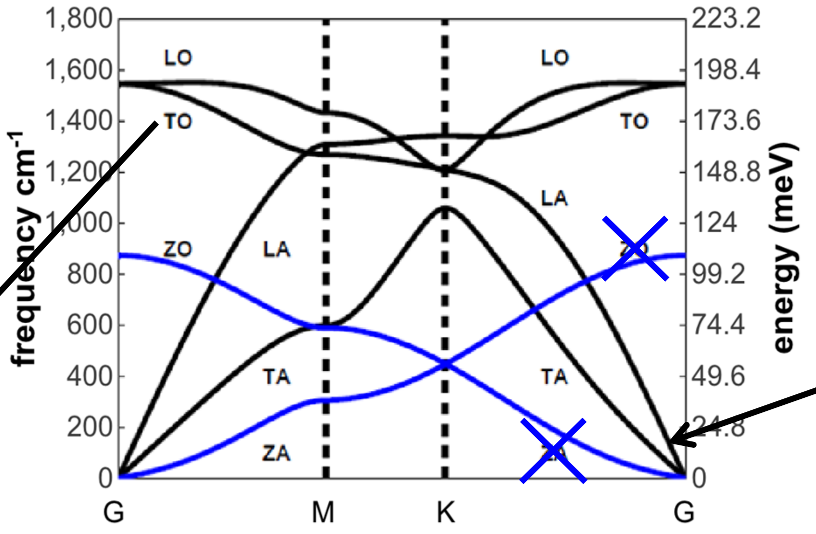
$$\boxed{S_I = 4Gk_B\langle T_e\rangle = 2\text{eI}\,\frac{\sqrt{3}}{4}}$$

Metallic sample : from meso to macro

… on increasing the bias voltage

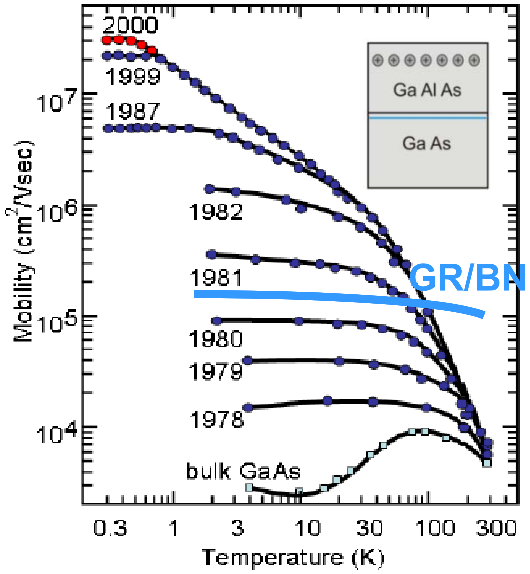


Phonon resistivity

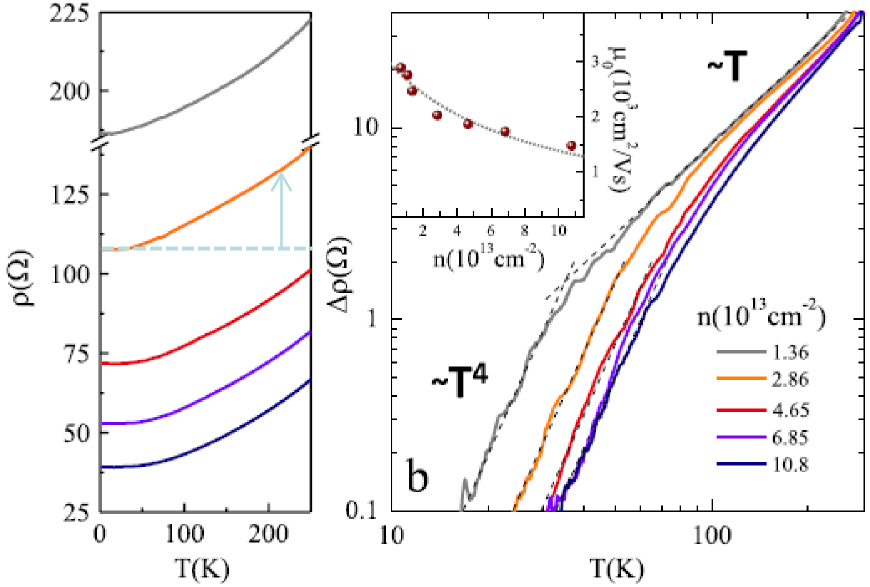


OP-phonons irrelevant

large AC-phonons velocity ($s = 2x10^4$ m/s)



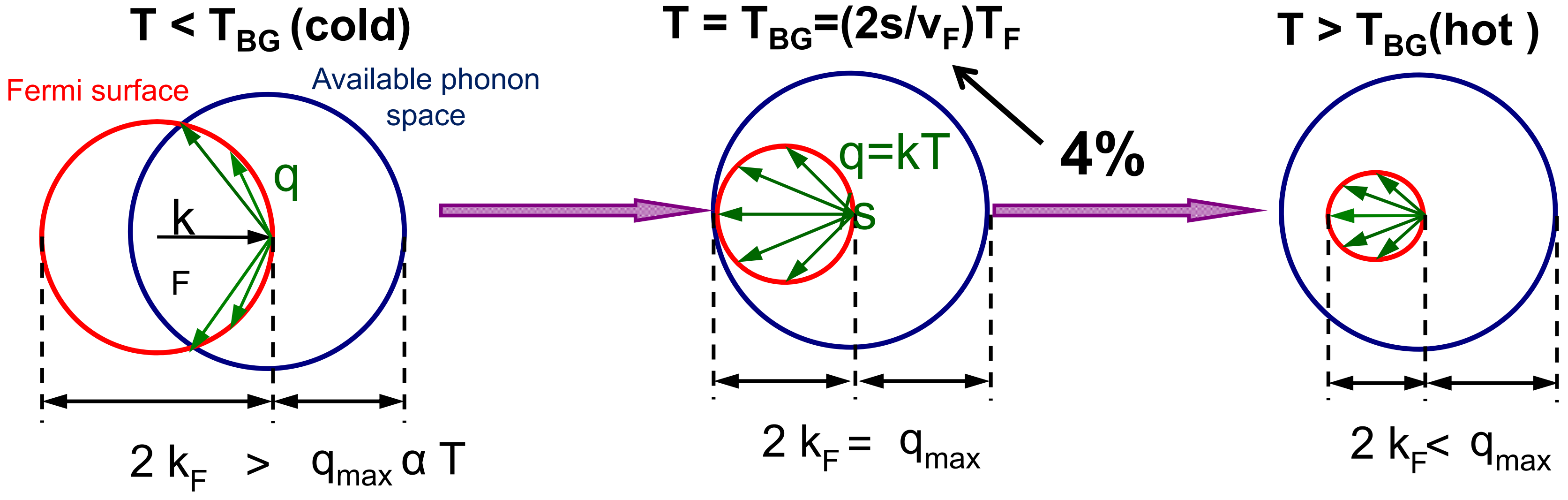
weak AC-phonons effect



Chen-Fuhrer / Nat. Nano (2008)
Efetov-Kim / Phys. Rev. Lett. (2010)

Phonon scattering : Bloch-Gruneisen temp.

$$T_F \approx 1000\,K \quad \leftrightarrow \quad T_{BG} \approx 40\,K$$



$T < T_{BG}$ (cold)

Fermi surface

Available phonon space

$2\ k_F\ >\ q_{max}\ \alpha\ T$

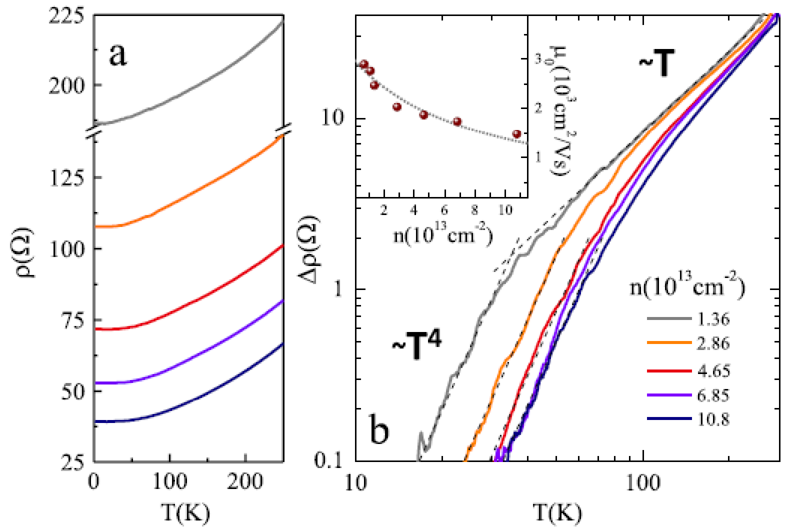
$T = T_{BG}=(2s/v_F)T_F$

4%

$2\ k_F =\ q_{max}$

$T > T_{BG}$(hot)

$2\ k_F <\ q_{max}$



Chen-Fuhrer / Nat. Nano (2008)
Efetov-Kim / *Phys. Rev. Lett. (2010)*

$$\Delta\rho(T_{ph} \ll \theta_{BG}) = \frac{8D^2 k_F}{\rho_m e^2 s\, v_F{}^2} \times f\left(\frac{T_{BG}}{T_{ph}}\right) \sim T^4$$

$$\Delta\rho(T_{ph} \ll \theta_{BG}) \sim const.\times\ T\ !!!\ \ ;\ \ const. \approx 0.1\Omega/K\ !!!$$

$$\mu_{ph}(300K) = 1/ne\Delta\rho \approx 2\times 10^5/n_{12}$$

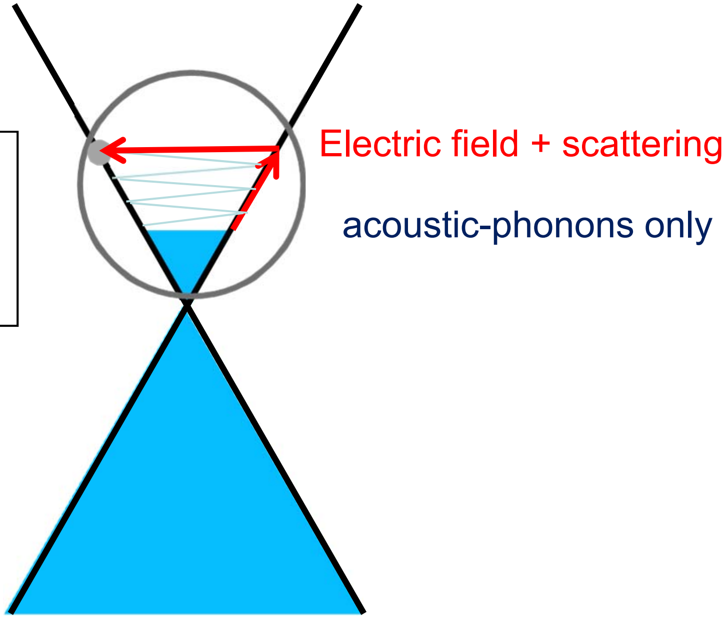
$$l_{ph}(300K) = \mu E_F/ev_F \approx 7\ \mu m\ /\sqrt{n_{12}}$$

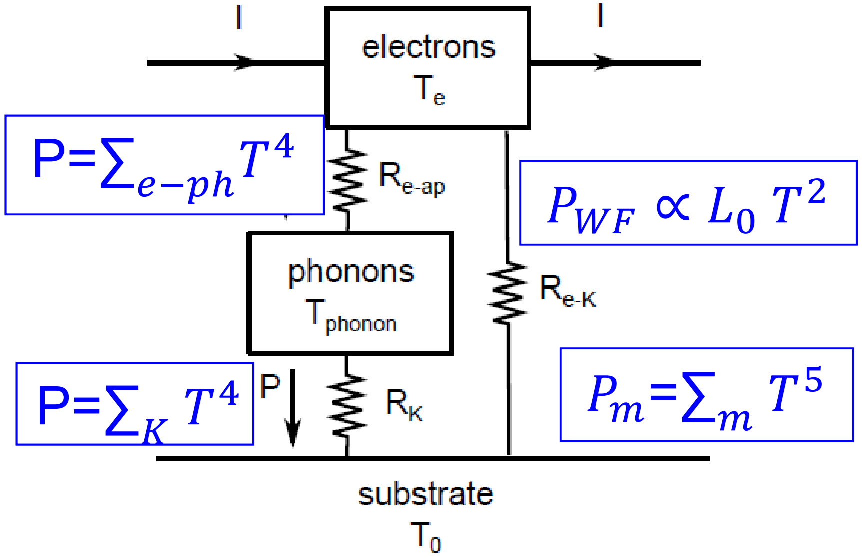
L. Wang et al. / Science 342 (2013) 614

Phonon relaxation / cooling

Joule heating and phonon cooling at 4K (cold phonons)

Graphene :
$V_F=10^6\ m/s$
$s/V_F=0.02$





$P=\Sigma_{e-ph}T^4$

$P_{WF} \propto L_0\ T^2$

$P=\Sigma_K\ T^4$

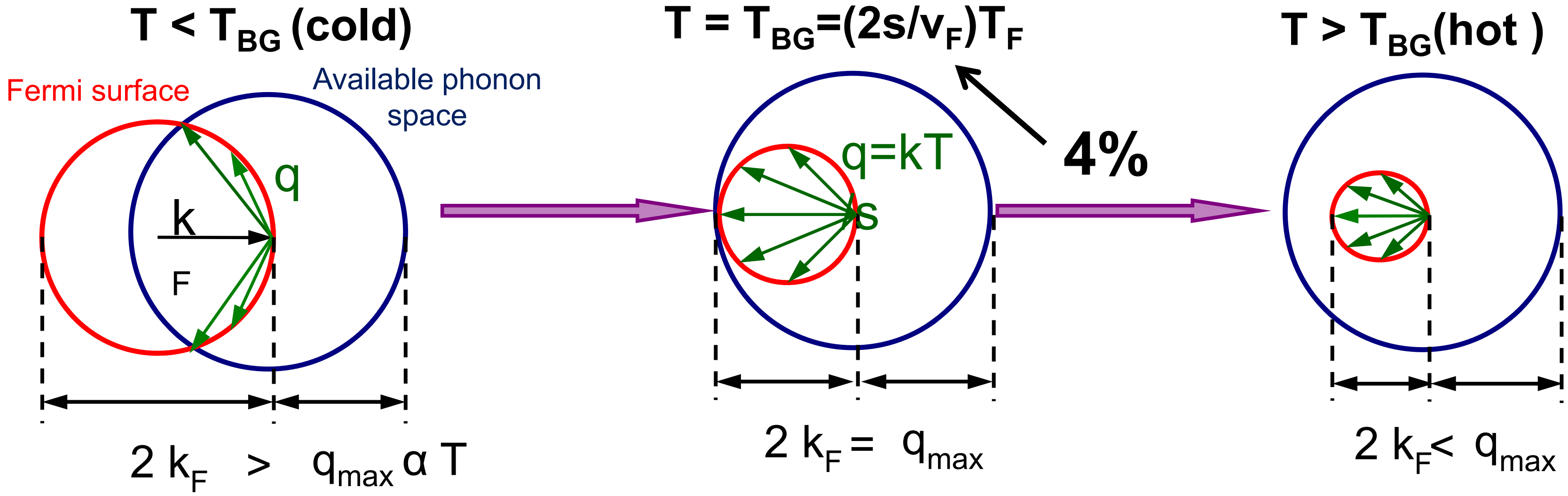
$P_m=\Sigma_m\ T^5$

Very weak AC-phonon coupling

$$\boxed{P_{graphene} = 10mW/m^2K^4 \times {T_e}^4 \ll P_{Kapitza} = 10W/m^2K^4 \times {T_{ph}}^4 \ll P_{metals} = 500\ W/m^2K^5 \times {T_e}^5}$$

Phonon scattering : Bloch-Gruneisen temp.

$$T_F \approx 1000\ K \quad \leftrightarrow \quad T_{BG} \approx 40\ K$$



$T < T_{BG}$ (cold)

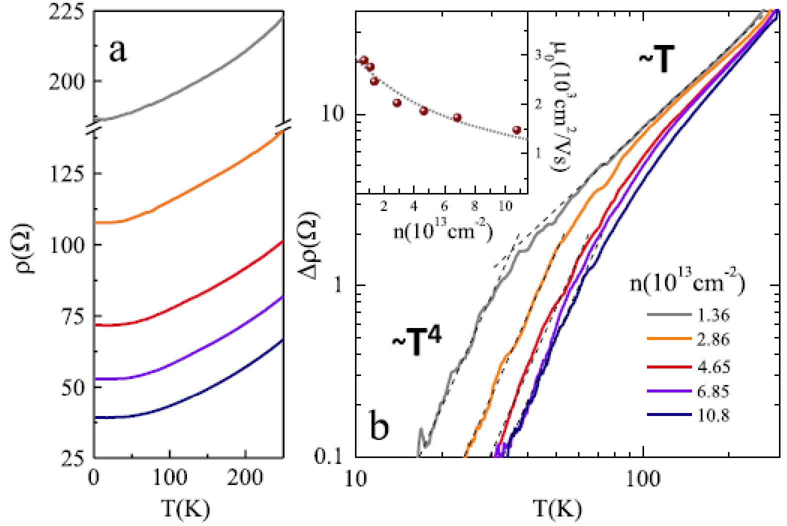
$T = T_{BG} = (2s/v_F)T_F$

$T > T_{BG}$(hot)

$2\ k_F\ >\ q_{max}\ \alpha\ T$

$2\ k_F = q_{max}$

$2\ k_F < q_{max}$



Chen-Fuhrer / Nat. Nano (2008)
Efetov-Kim / *Phys. Rev. Lett. (2010)*

$$\Delta\rho(T_{ph} \ll \theta_{BG}) = \frac{8D^2 k_F}{\rho_m e^2 s\ v_F{}^2} \times f\left(\frac{T_{BG}}{T_{ph}}\right) \sim T^4$$

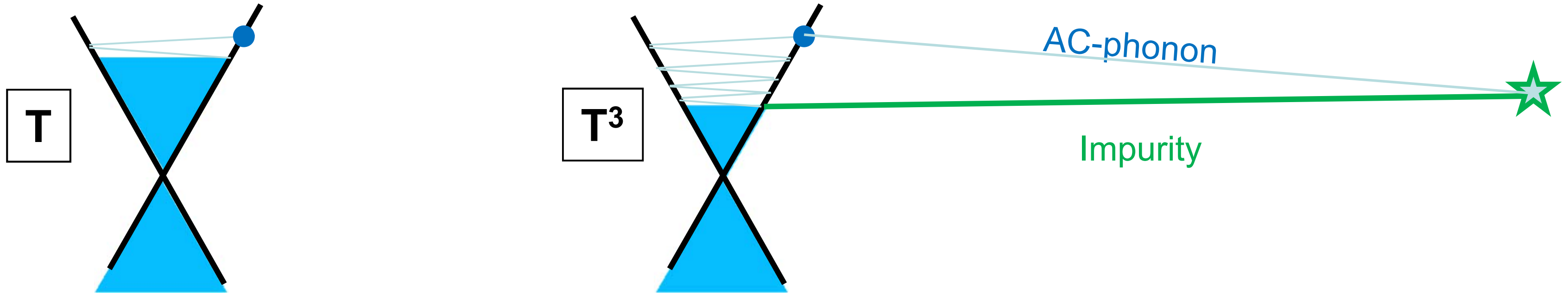
$$\Delta\rho(T_{ph} \ll \theta_{BG}) \sim const.\times\ T\ !!!\ \ ;\ \ const. \approx 0.1\Omega/K\ !!!$$

$$\mu_{ph}(300K) = 1/ne\Delta\rho \approx 2\times 10^5/n_{12}$$

$$l_{ph}(300K) = \mu E_F/ev_F \approx 7\ \mu m/\sqrt{n_{12}}$$

L. Wang et al. / Science 342 (2013) 614

Phonon relaxation (hot phonons)



Ordinary electron-phonon

3-body electron-phonon-impurity

Heat equation

$$\frac{L_o}{2R}\frac{L^2\partial^2 T^2(x)}{\partial x^2} = -\frac{V^2}{R} + P_{phonons}$$

Cold phonon cooling

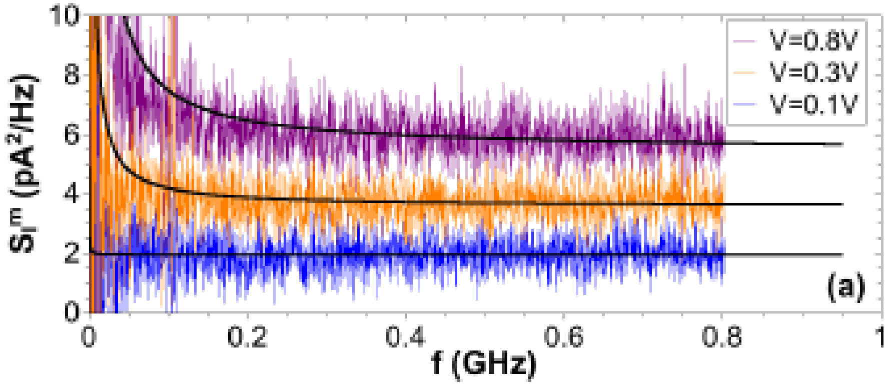
$$P_{ph}(T_{ph} \ll \theta_{BG}) = \frac{\pi^2 D^2 {k_B}^4 E_F}{15\rho_m \hbar^5 s^3 {v_F}^3} \times \left({T_e}^4 - {T_{ph}}^4\right)$$

Supercollisison regime

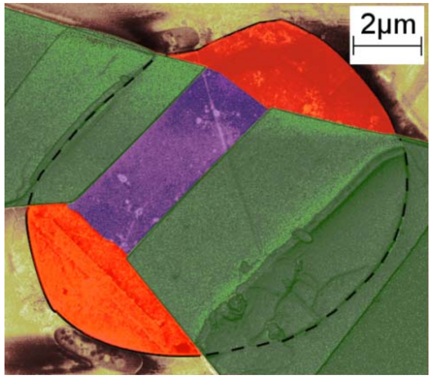
$$P_{ph}(T_{ph} \gg \theta_{BG}) = \frac{1}{k_F l} \times \frac{9.62 D^2 {k_B}^3 {E_F}^2}{8\pi^2 \rho_m \hbar^5 s^2 {v_F}^4} \times \left({T_e}^3 - {T_{ph}}^3\right)$$

RF noise measurement

Thermal + 1/f noise

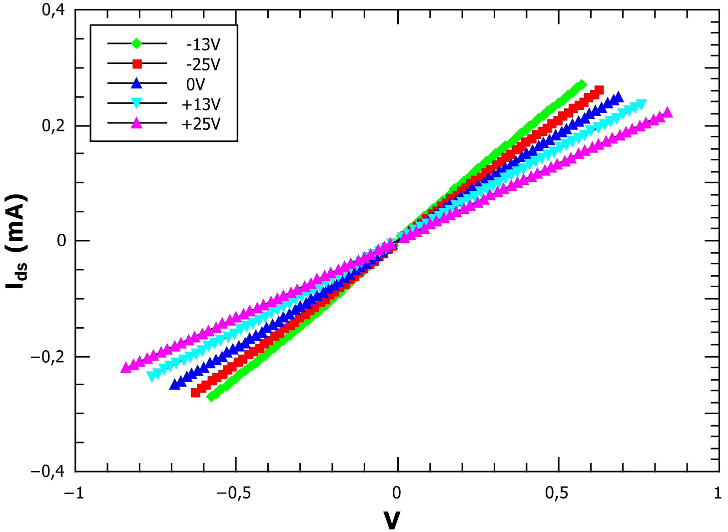


diffusive G/hBN sample

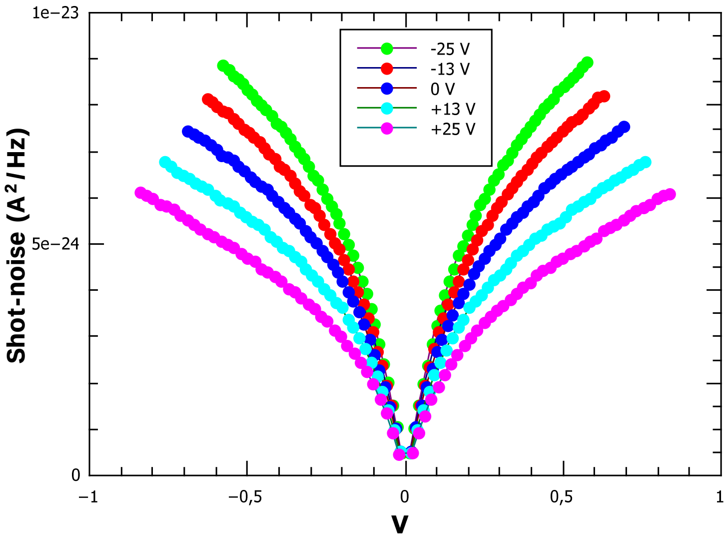


very-BN™
hBN powder
by St Gobain

linear I-V's (diffusive)



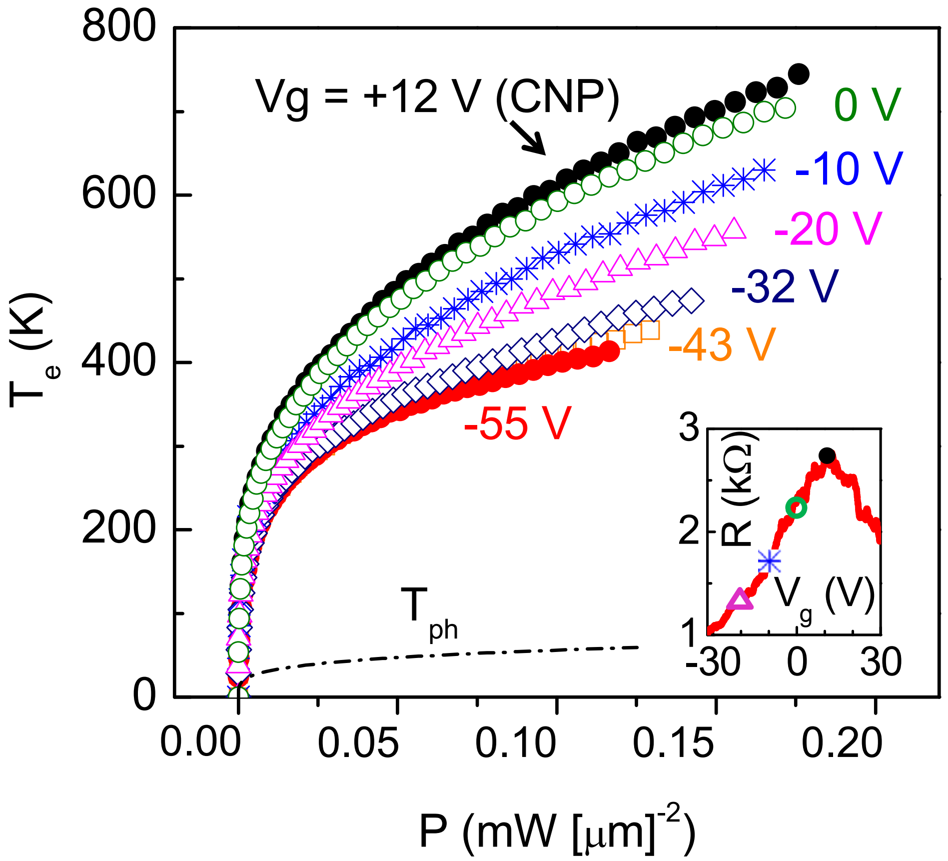
noise: from linear to sublinear

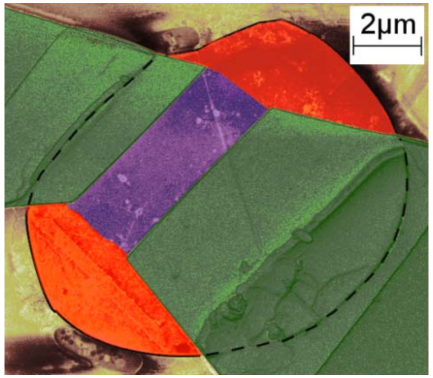


A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

Electronic temperature measurement

$$\langle T_e \rangle \equiv R\, S_I / 4k_B$$

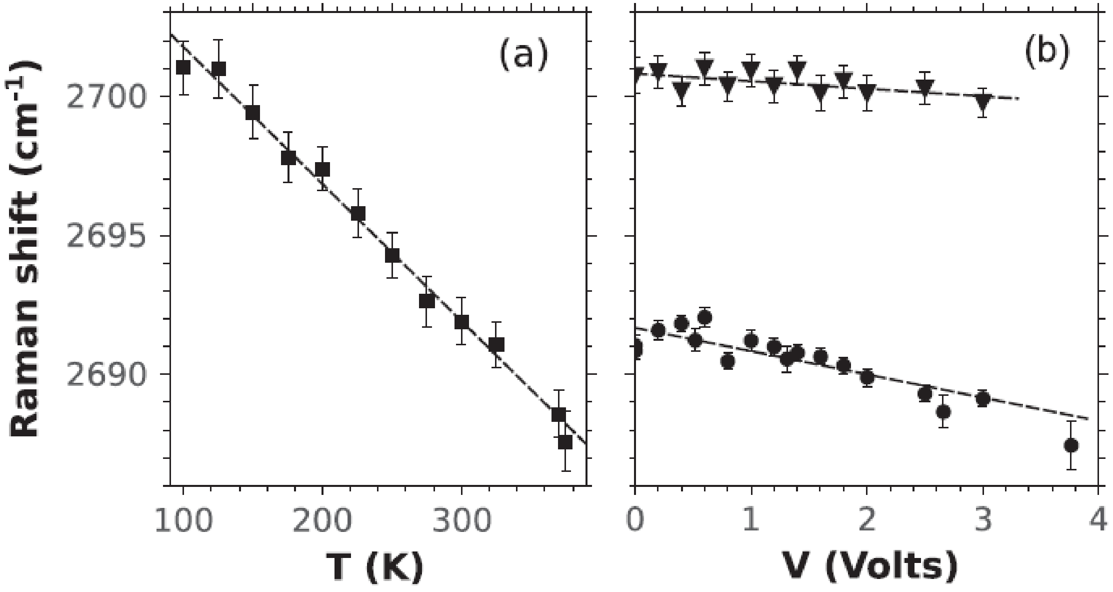


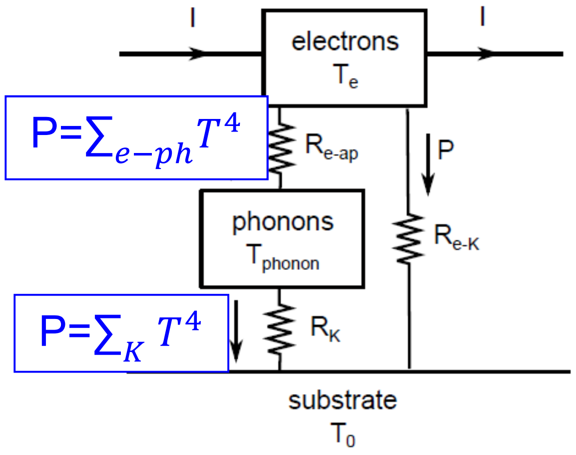


A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

Checking the phonon temperature

Temperature dependent Raman shift of 2D Peak





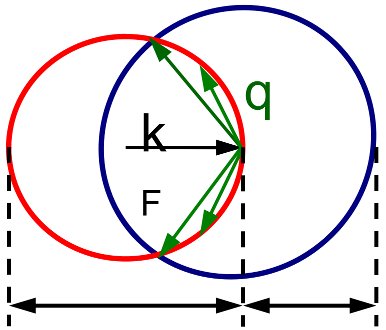
$$T_{ph} \ll T_e \quad and \quad T_{ph}(P) \sim T_{BG} \quad (graphene\ is\ so\ kind\ to\ us)$$

A. *Betz et al. / Phys. Rev. Lett. 109 (2012) 056805*
B. *Collab. C. Voisin group*

Data analysis : Bloch-Gruneisen regime

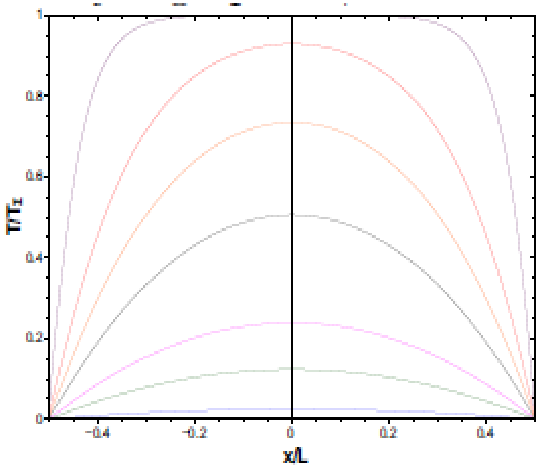
GRAPHENE FLAGSHIP

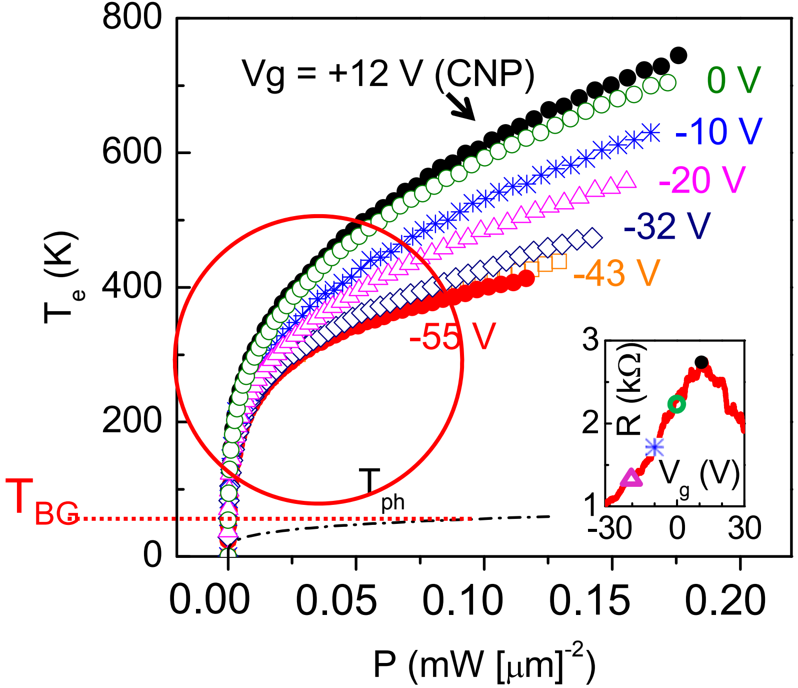
$T < T_{BG}$ (cold)

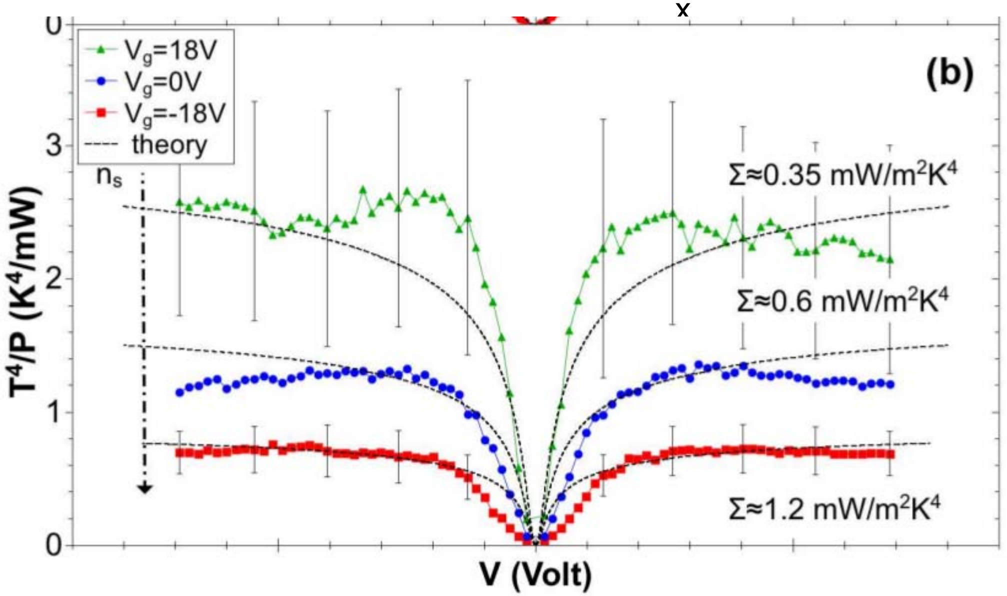


$2\, k_F \ > \ q_{max} \, \alpha \, T$

$$\frac{L_o}{2R}\frac{L^2\partial^2 T^2(x)}{\partial x^2} = -\frac{V^2}{R} + \sum T_e{}^4$$





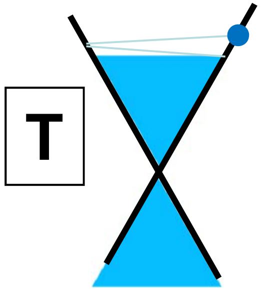


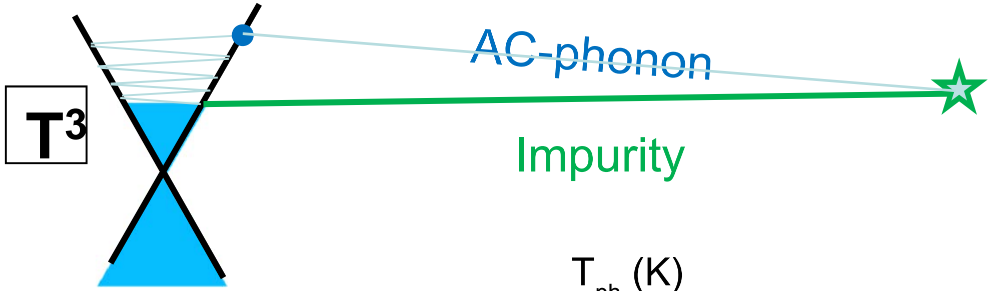
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

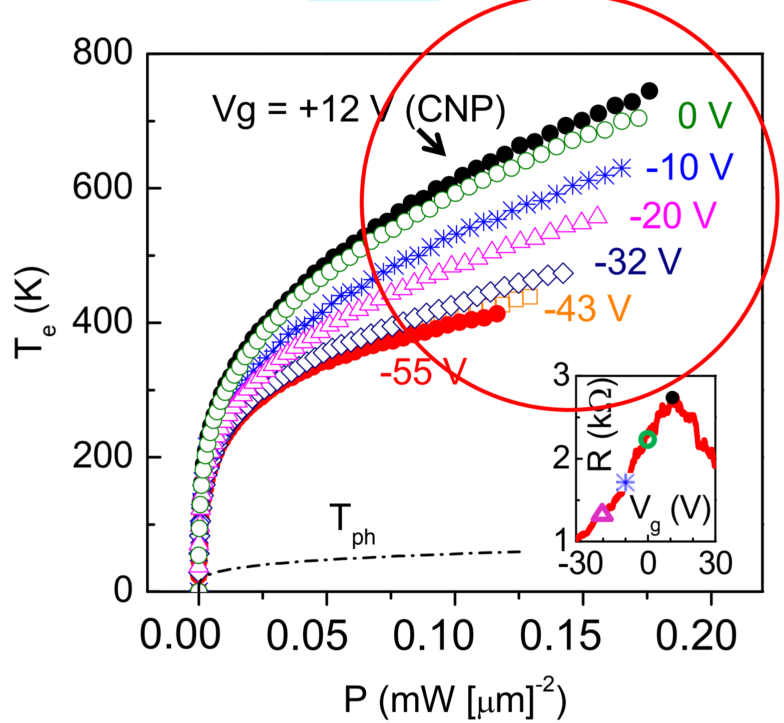
Hot phonons : supercollisions

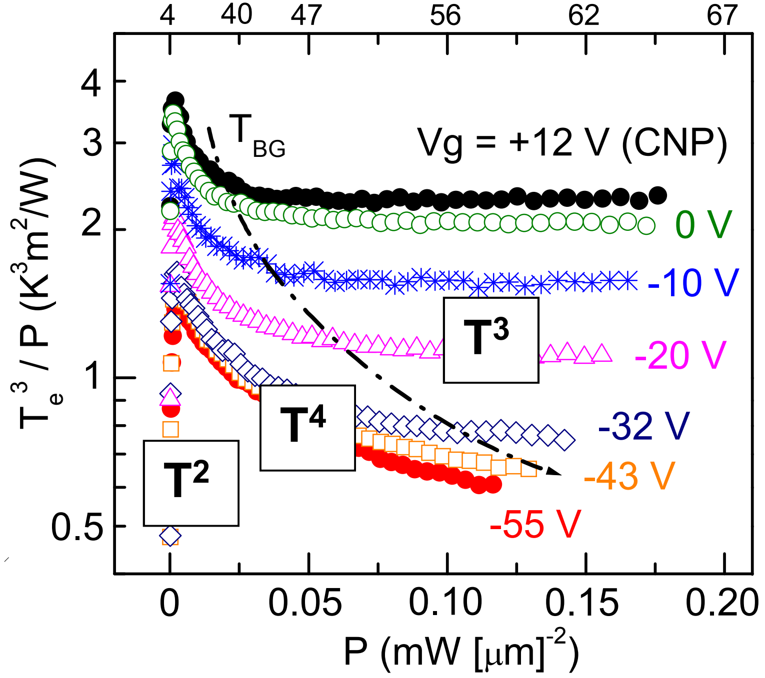
Ordinary electron-phonon collision

3-body electron-phonon impurity





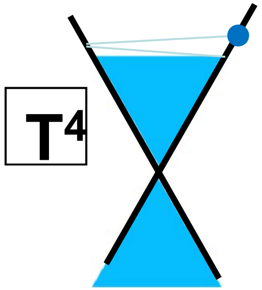




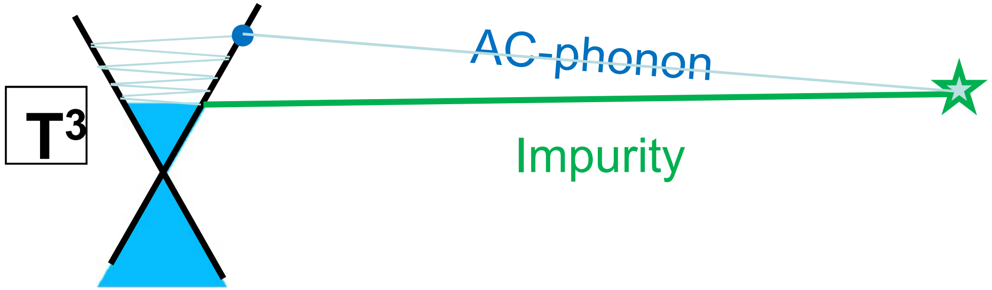
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805
A. Betz et al. / Nat. Phys. 9 (2012) 109

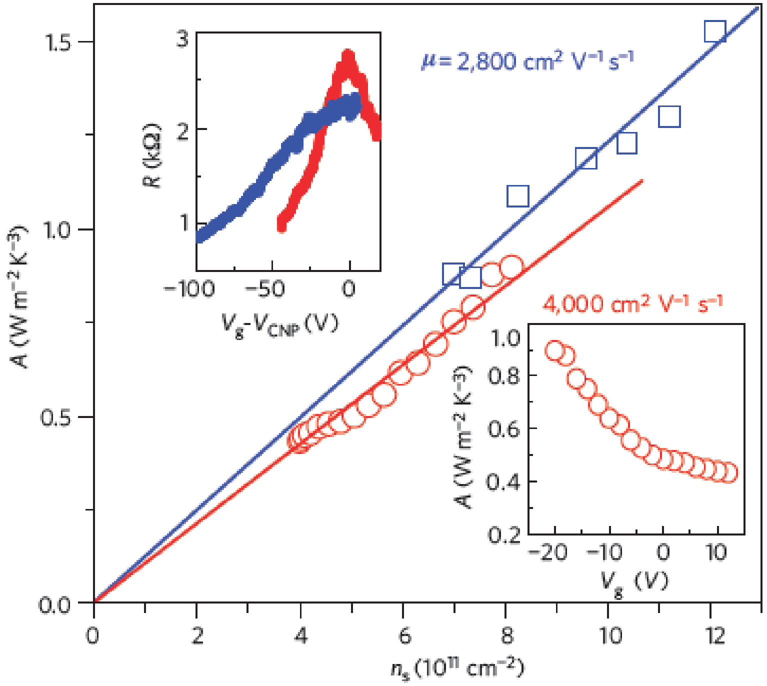
Supercollisons regime

Ordinary electron-phonon collision



3-body electron-phonon-impurity





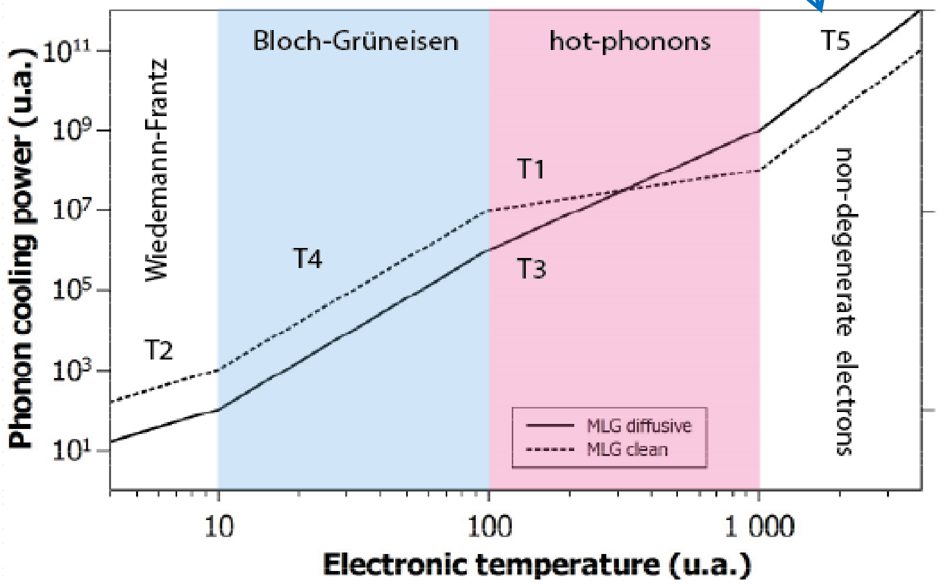
$$P_{ph} = \frac{1}{k_F l} \times \frac{9.62 D^2 k_B{}^3 E_F{}^2}{8\pi^2 \rho_m \hbar^5 s^2 v_F{}^4} \times \left(T_e{}^3 - T_{ph}{}^3\right)$$

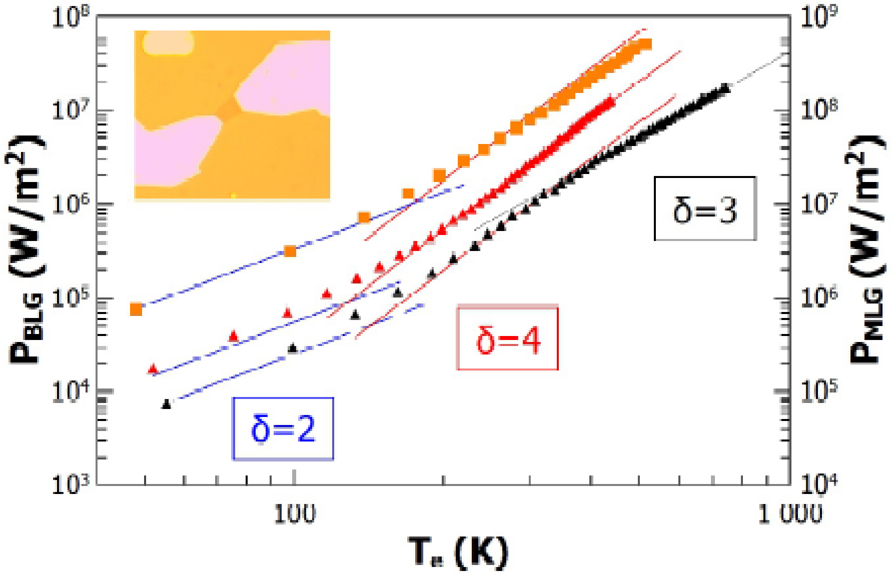
A. Betz et al. / Nat. Phys. 9 (2012) 109

Song-Levitov / PRL (2013)

The full AC-Phonon scenario

Suspended G : Antti Laitinen poster !!



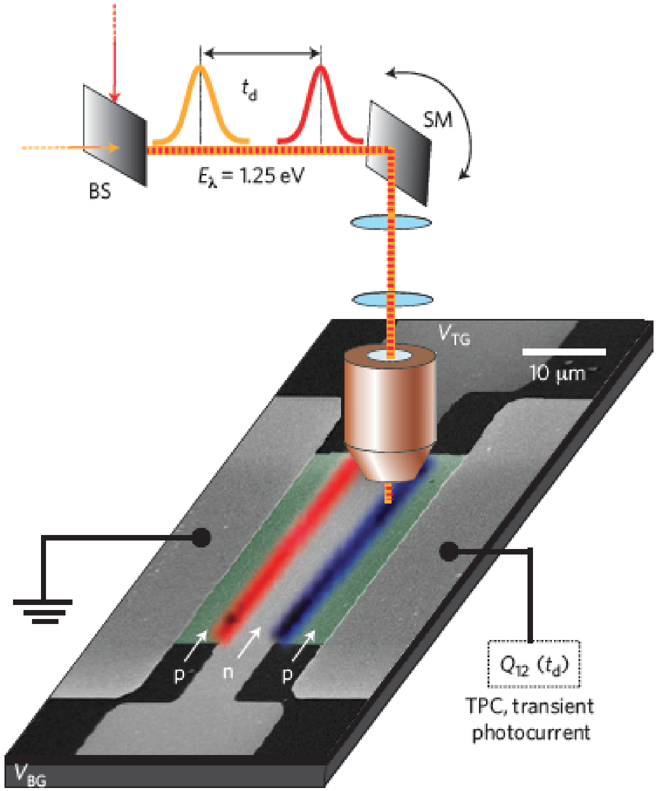


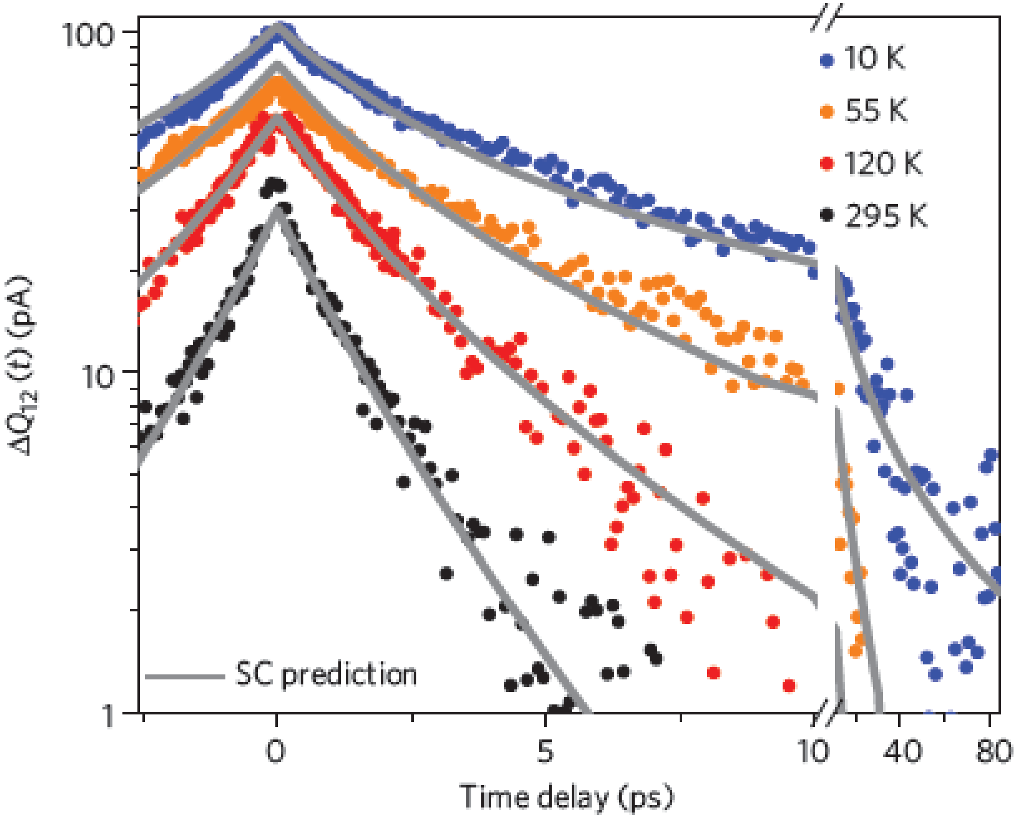
C. Voisin and B. Plaçais / special issue “hot carriers in graphene”, *J. Phys.: Condens. Matter 27 (April 2015)*
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805
A. Betz et al. / Nat. Phys. 9 (2012) 109
A. Laitinen et al. / Nano Lett..14 (2012) 3009.

Supercollisions are also seen in optics

GRAPHENE FLAGSHIP

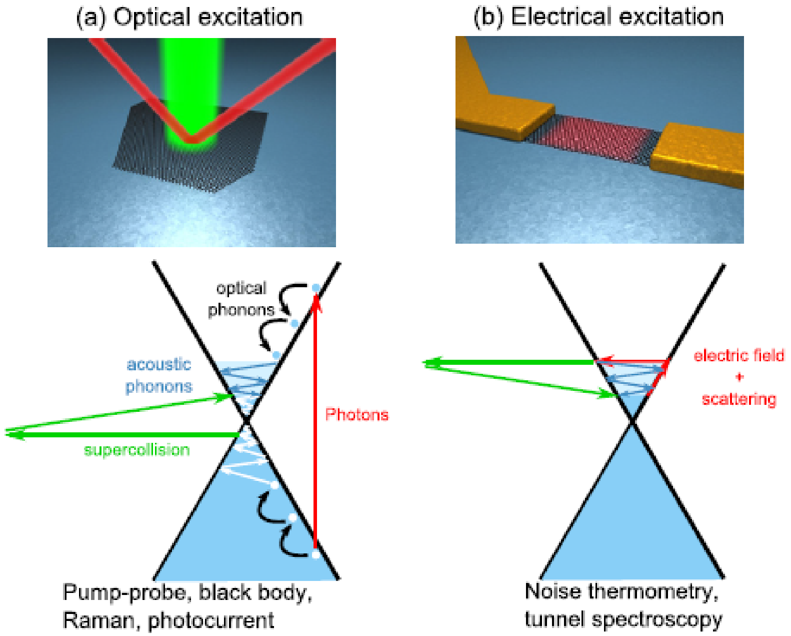
Pump-probe experiment at Cornell (Graham et al., Nat. Phys 2013)





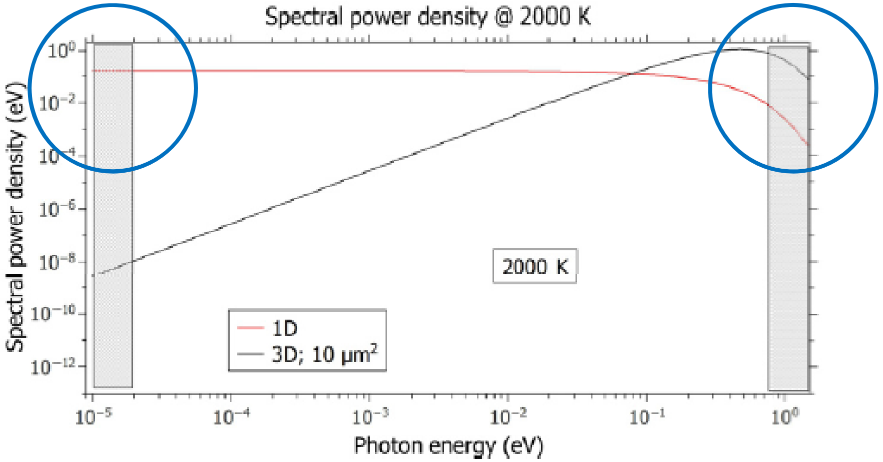
$$\gamma T_e \frac{\partial T_e(x)}{\partial t} - \cancel{\frac{L}{2RW}\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial^2 T_e^2(x)}{\partial x^2}} = \cancel{\frac{V^2}{RLW}} - P(T_e, T_{ph})$$

Phonon cooling optoelectronics



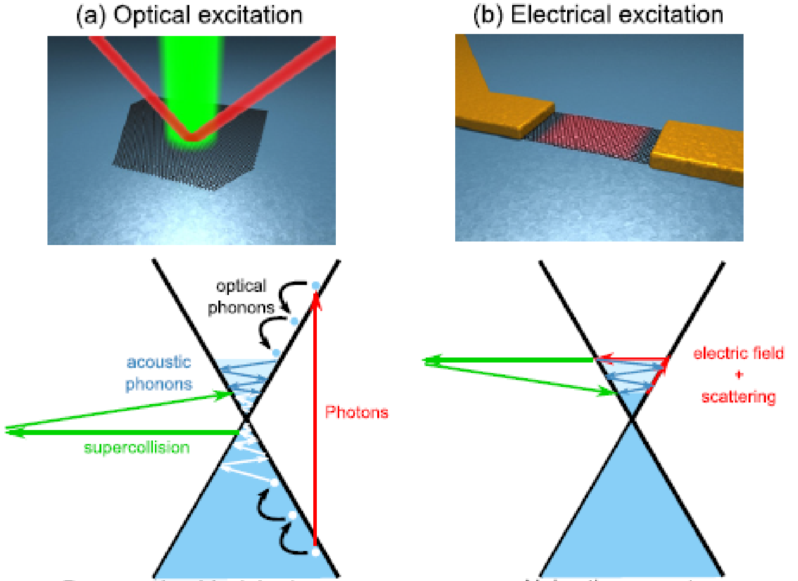
RF Thermal noise

Black-body (tail)



Collaboration with Ch. Voisin's Optics group at LPA

Phonon cooling optoelectronics

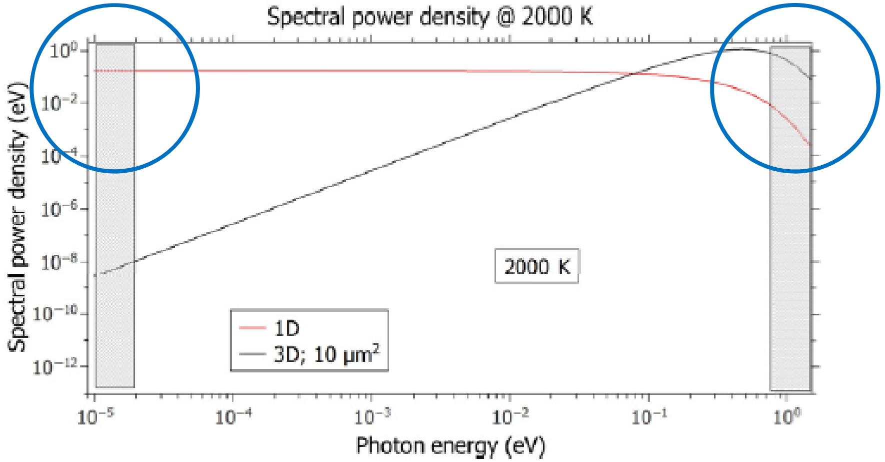


Pump-probe, black body, Raman, photocurrent

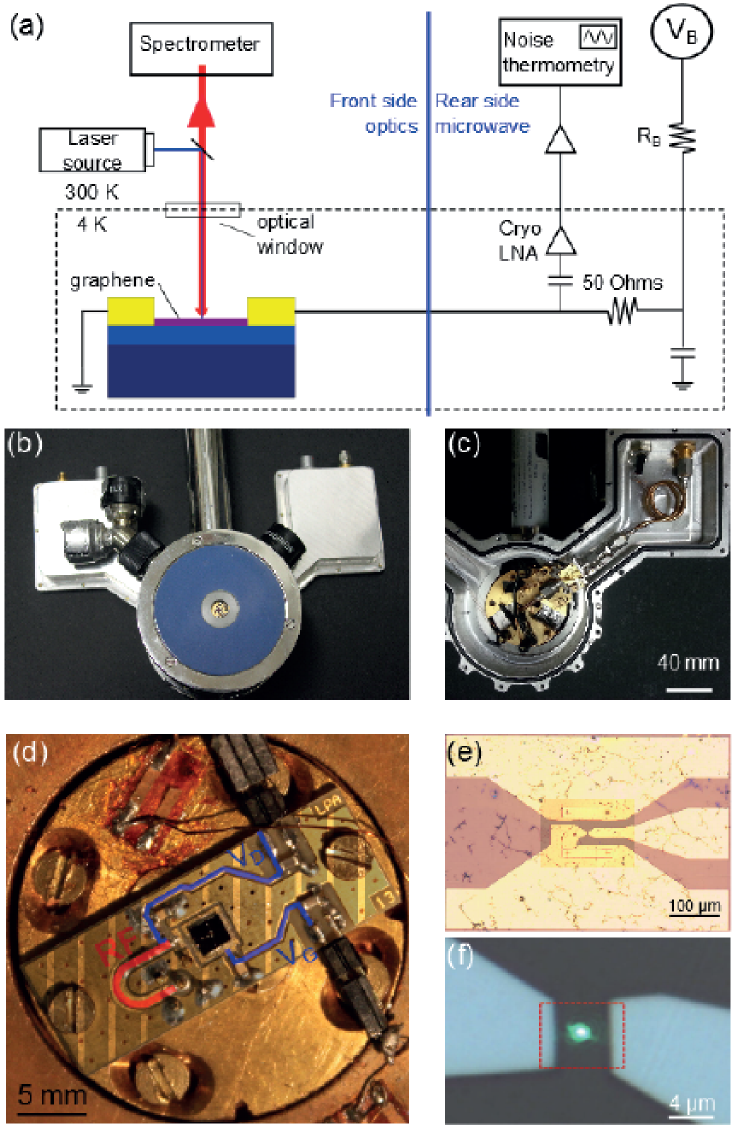
Noise thermometry, tunnel spectroscopy

RF Thermal noise

Black-body (tail)



« Janus » setup



Collaboration with Ch. Voisin's Optics group at LPA

Comparing RF and Optical C-power

Black-body spectrum (tail)

RF Thermal noise

J. Phys.: Condens. Matter **27** (2015) 000000 — D Brunel *et al*

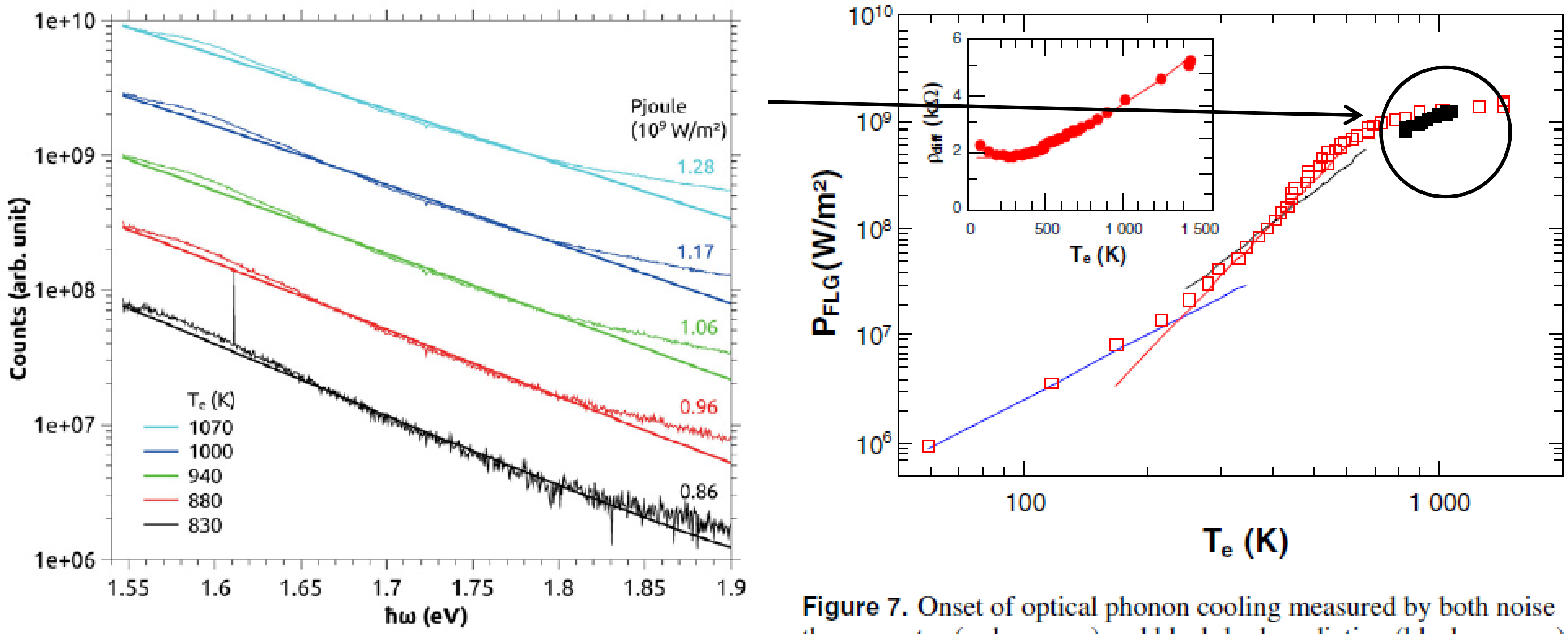
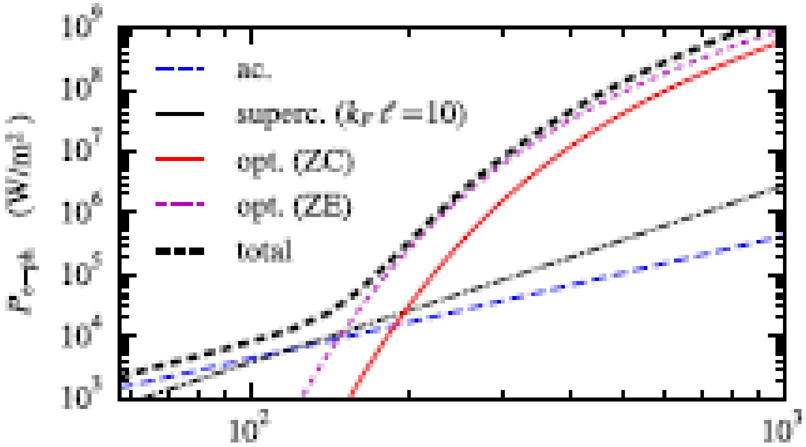


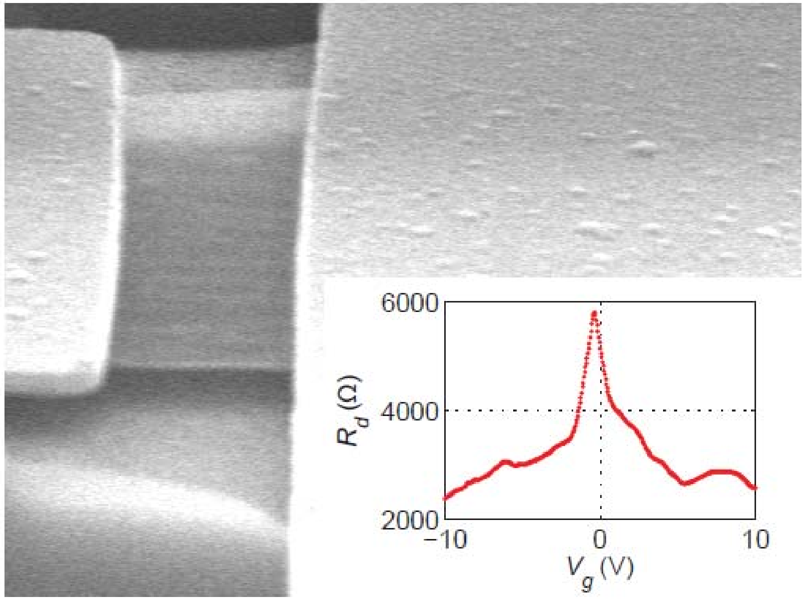
Figure 7. Onset of optical phonon cooling measured by both noise thermometry (red squares) and black-body radiation (black squares).

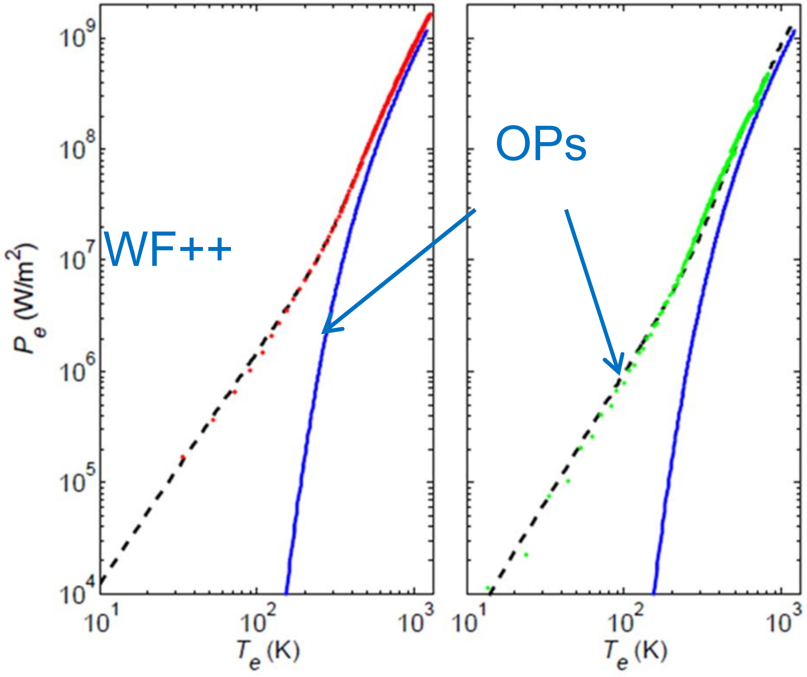
Collab. Ch. Voisin's Optics group at LPA

Optical phonon cooling (bilayer)

Suspended bi-layer graphene :
Low carrier density
Suppressing AC-phonon cooling







WF++

OPs

A. Laitinen et al. / Phys. Rev. B, Rapid Comm. (2015) in press

Applications of hot electron effect ?

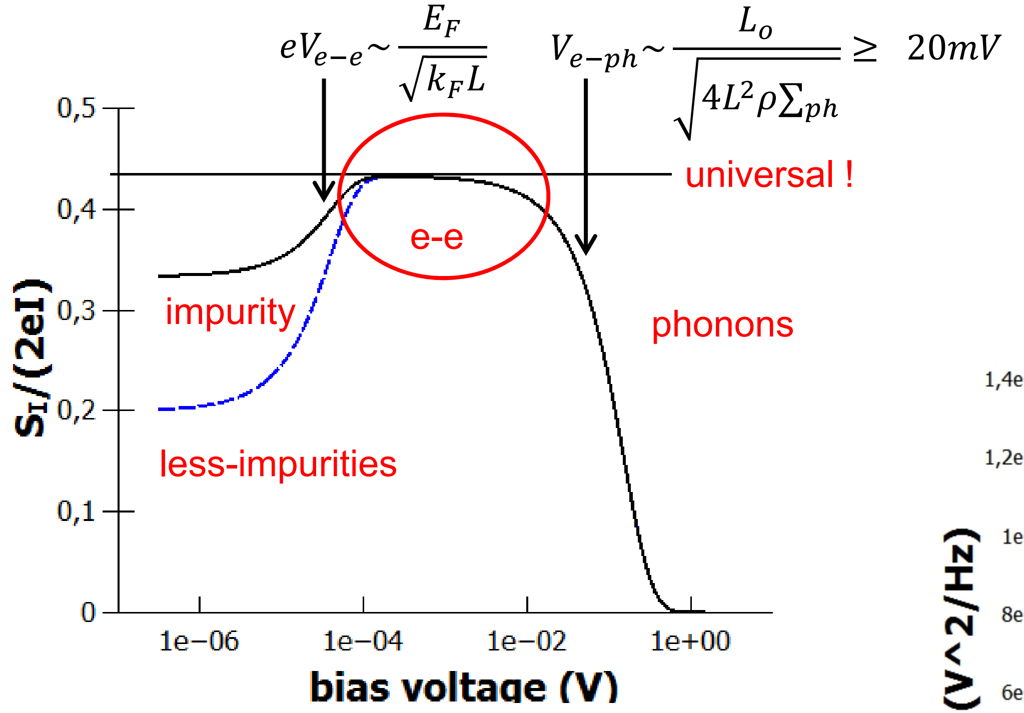
applications

Applications of the hot electron effects ?

- THz-UV bolometers
- Noise standard (for scientists only ?)
- LNA's

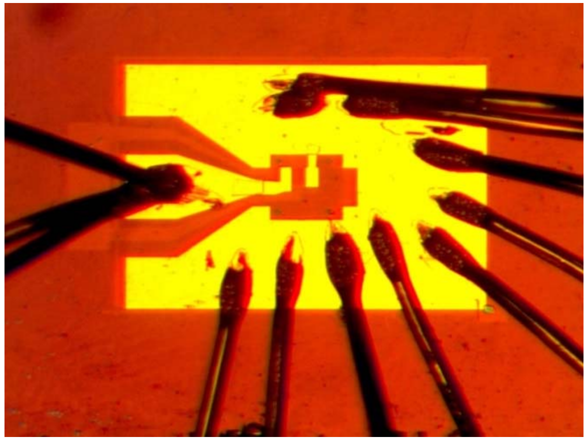
T^2 - hot-electrons as a noise standard

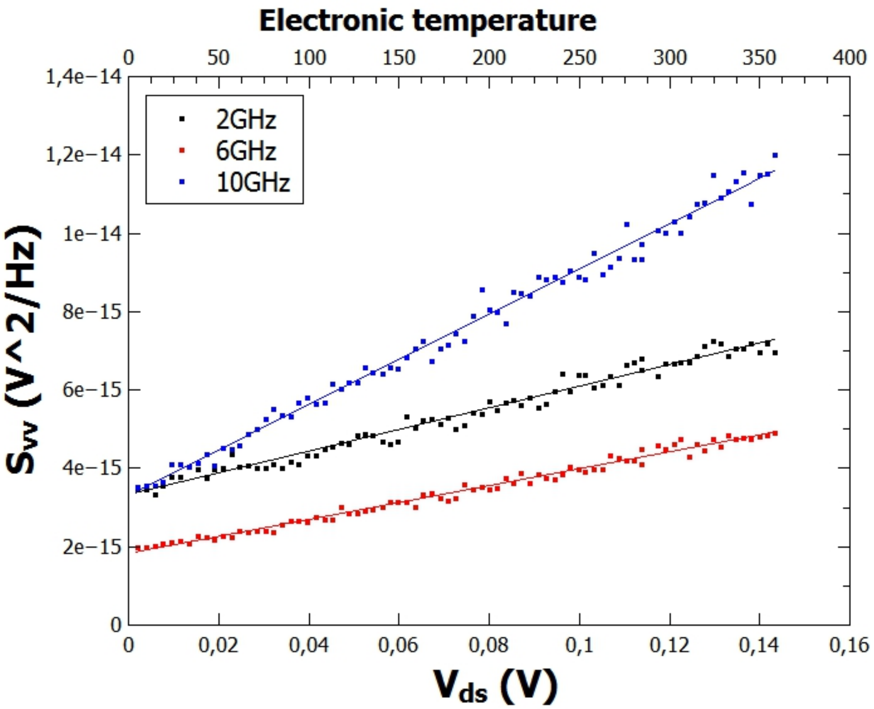
Short diffusive graphene



$$eV_{e-e} \sim \frac{E_F}{\sqrt{k_F L}} \qquad V_{e-ph} \sim \frac{L_o}{\sqrt{4L^2 \rho \Sigma_{ph}}} \geq 20mV$$

$$\boxed{2k_B T_e = \frac{\sqrt{3}}{4} \times eV}$$

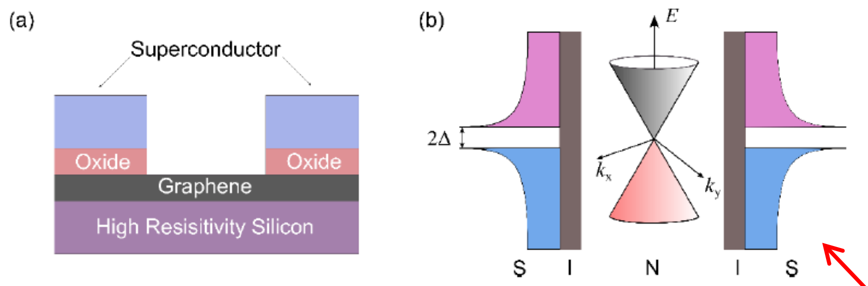


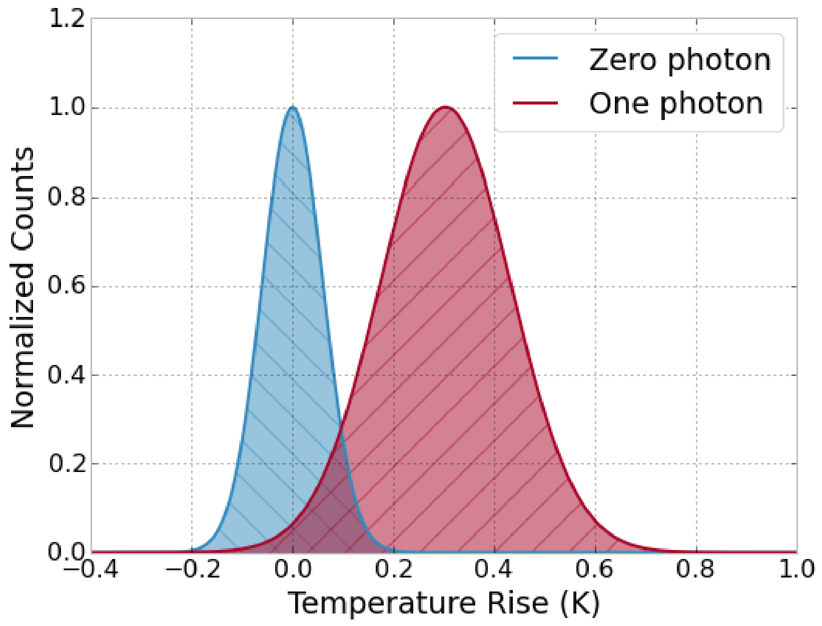


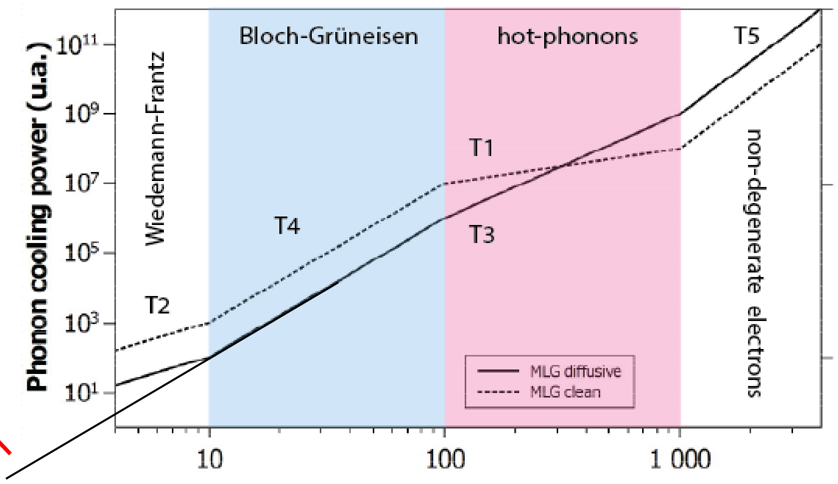
T^4 - Bloch-Gruneisen for THz detectors

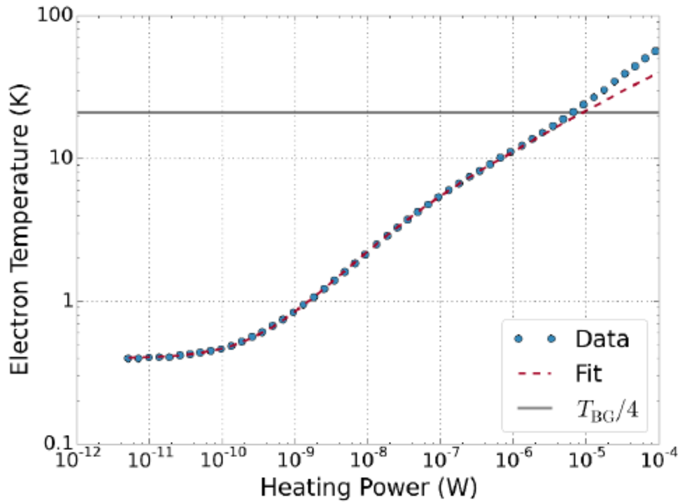
GRAPHENE FLAGSHIP

THz photo-detectors at Yale, etc…



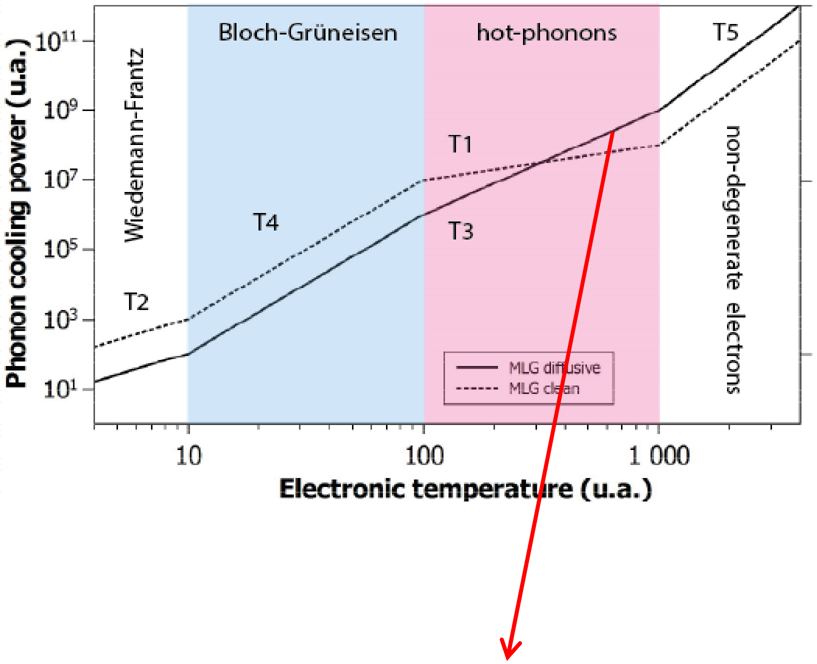






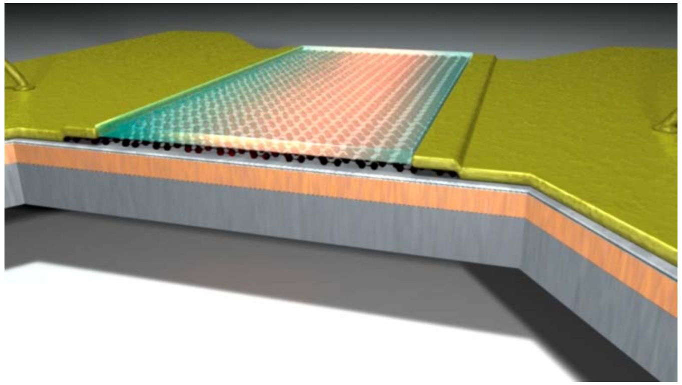
C B McKitterick et al. / special issue “hot carriers in graphene”, *J. Phys.: Condens. Matter 27 (2015)*

T^4 – supercollisions for LNA's, Optics ...



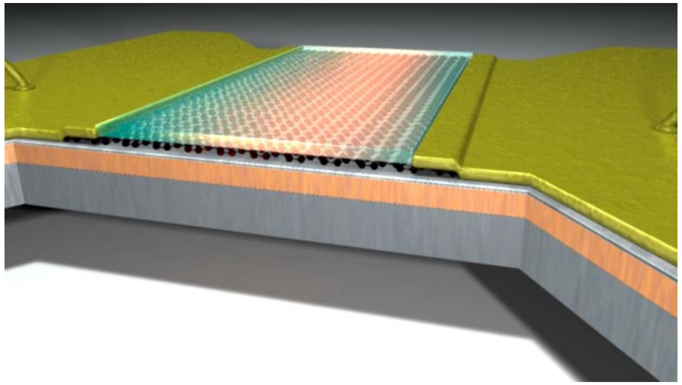
$$\boxed{T_N = \frac{T_e}{Gain^2} \leq 300K}$$

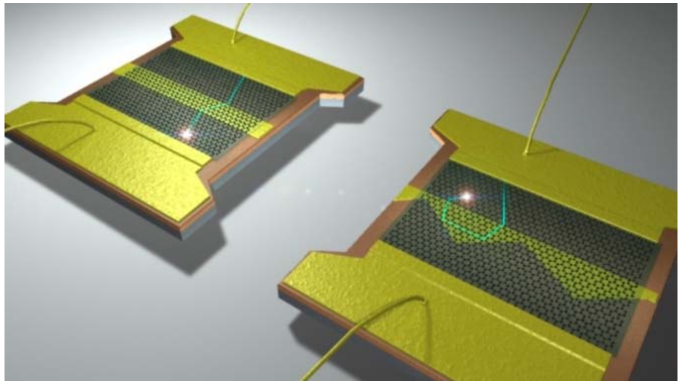
Conclusions on noise (L1)



- Electron-phonon in graphene is weak for ACs and strong for OPs
- Hot electron effects are prominent
- Next : investigate OP-cooling, SPP-cooling etc....

HF-Graphene Electronics





noise (L1)

(electron-phonon)

ballistic's (L2)

(Dirac Fermion Optics)

Bernard Plaçais

placais@lpa.ens.fr

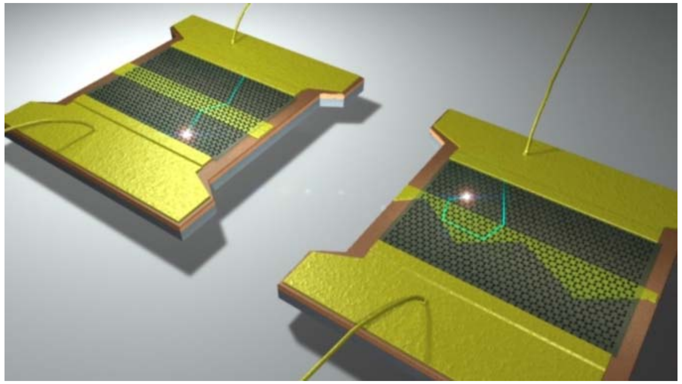
European
Commission

L2 : Ballistic graphene devices

Ballistic electronics is possible thanks to weak e-ph scattering (l_{ph}~2 μm at T_e~1000K)

Question : How can we exploit it ?

L2 : Ballistic graphene devices



- Motivation : Dirac Fermion Optics
- Ballistic graphene and junctions
- Ballistic graphene FETs
- Conclusions

Vasalego lens and splitters (proposal)

Relies negative refraction index (and a point source) : $\sin\varphi = -\left(k_n/k_p\right)\sin\theta$

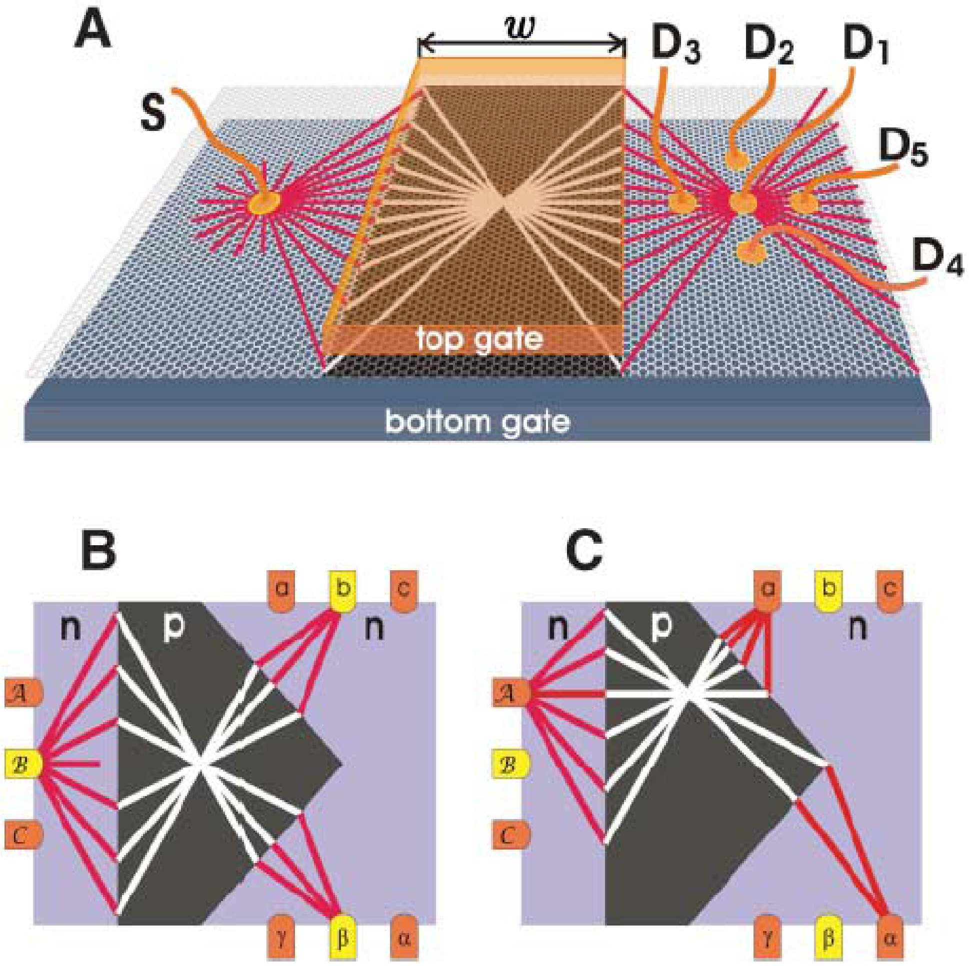
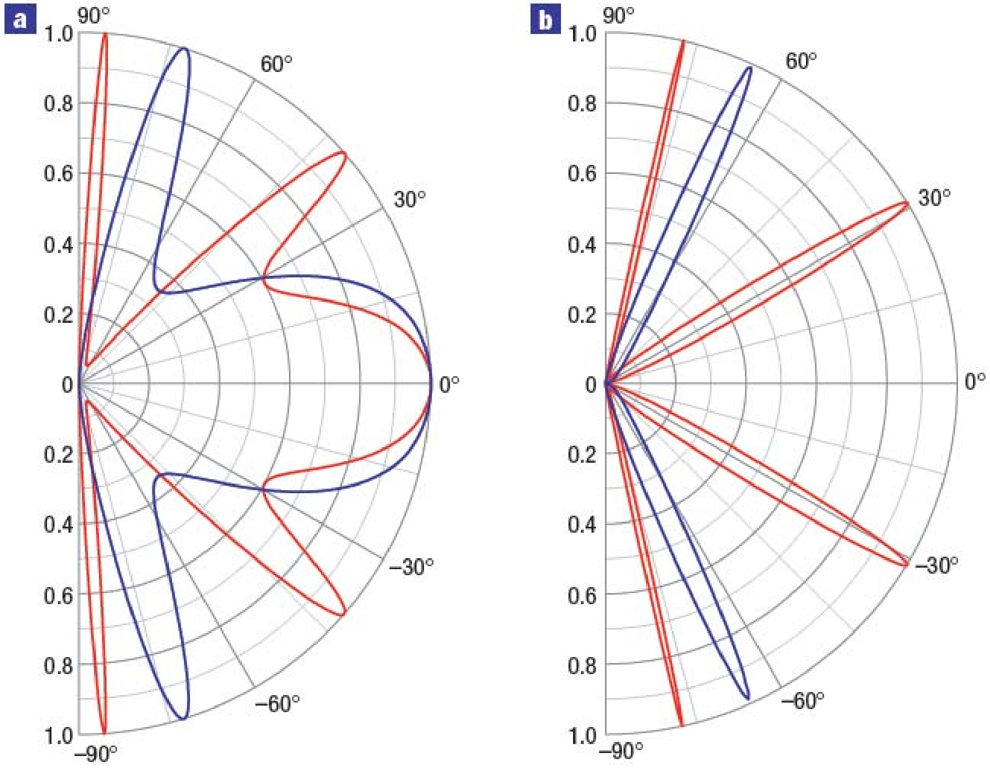


Fig. 4. (**A**) Electron Veselago lens and (**B** and **C**) prism-shaped focusing beam splitter in the ballistic *n-p-n* junction in graphene-based transistor.

V.V. Cheianov, V. Falko, B.L. Altshuler / Science 315 (2007) 1252

Refraction at p-n junctions



Single-layer

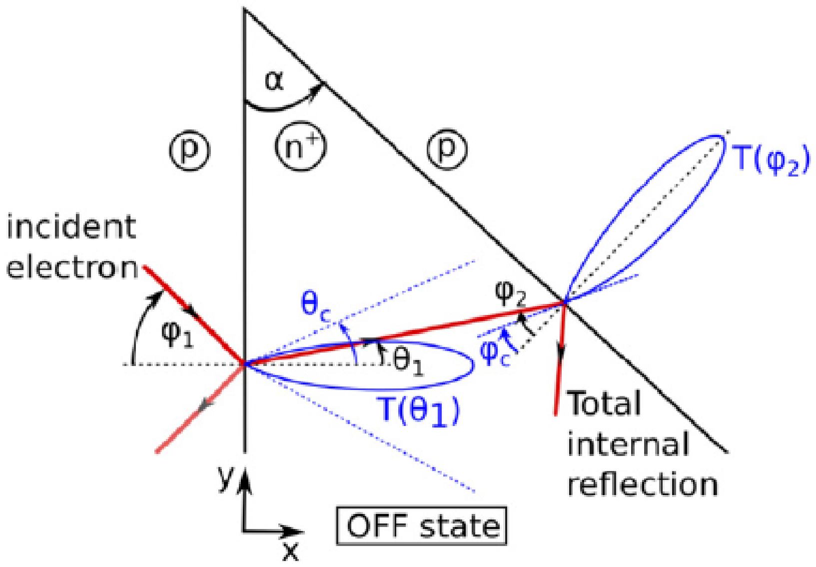
Bi-layer

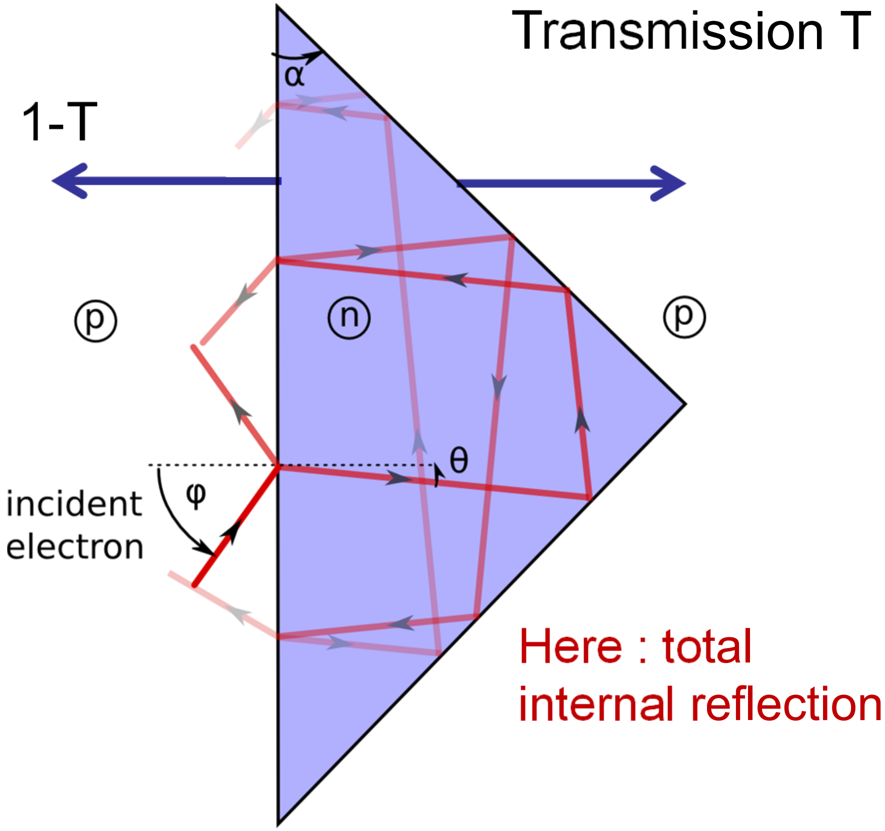
M.I. Katsnelson, K. Novoselov, A. Geim / Nat. Phys. 2 (2006) 620

Klein tunneling reflector (easier)

Relies on large refraction index contrast

$$\boxed{\sin\varphi = -\left(k_n/k_p\right)\sin\theta}$$



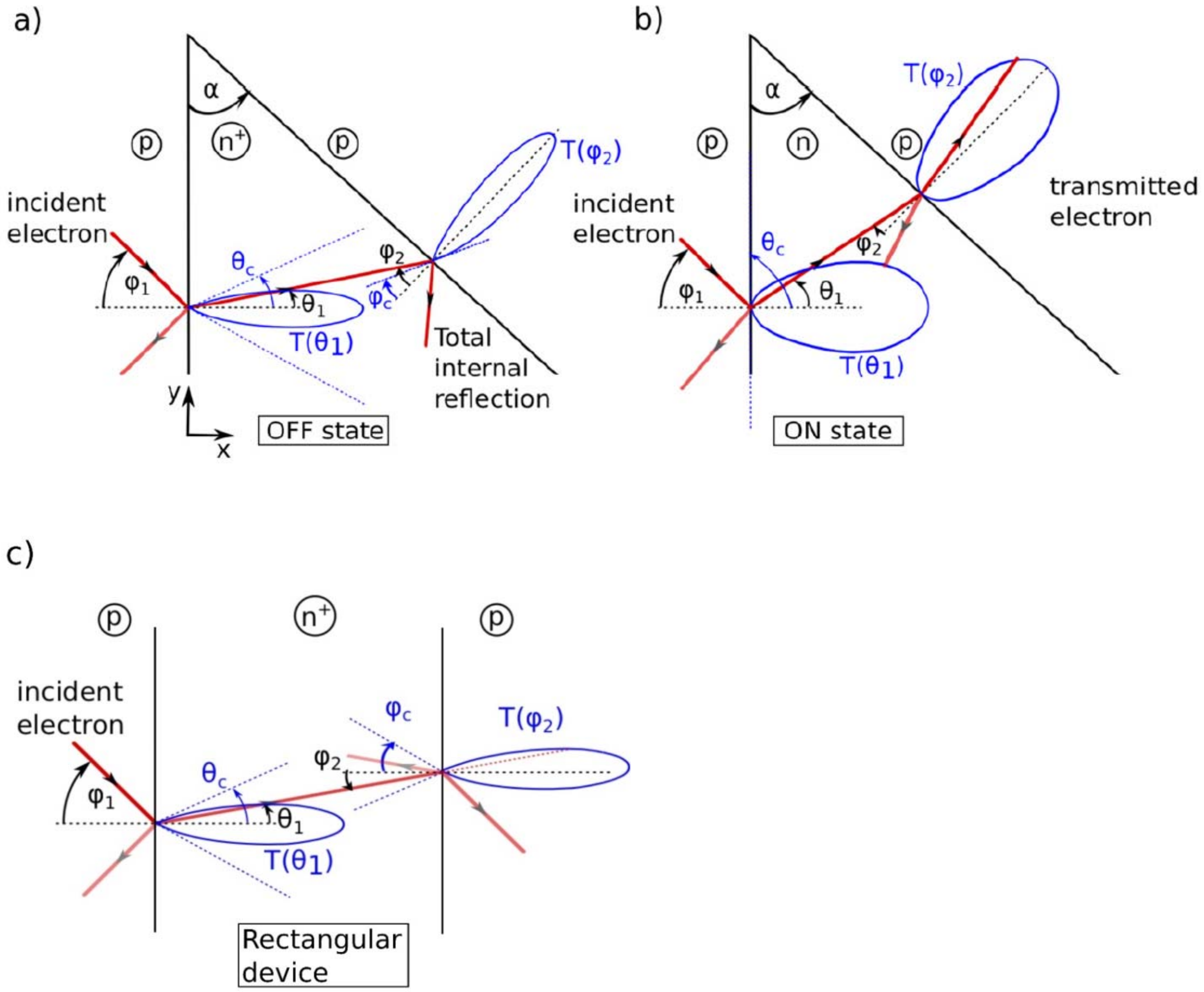


Here : total internal reflection

Q. Wilmar et al. / 2D Materials 1 (2014) 011006

Klein tunneling reflector (easier)

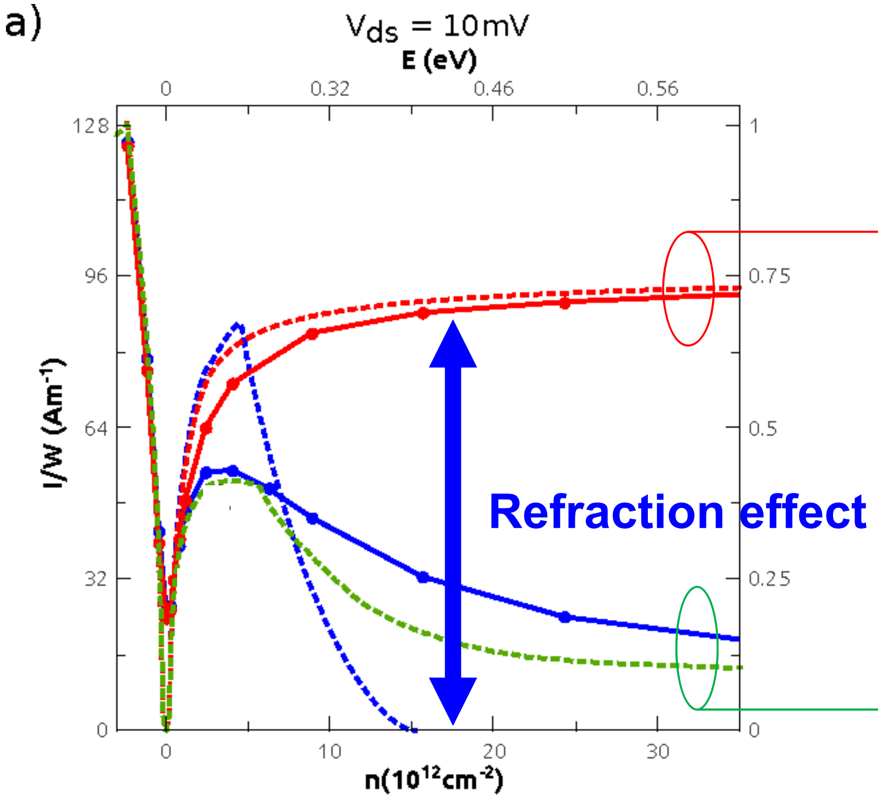
Relies on large and tunable refraction index contrast $\boxed{\sin\varphi = -\left(k_n/k_p\right)\sin\theta}$



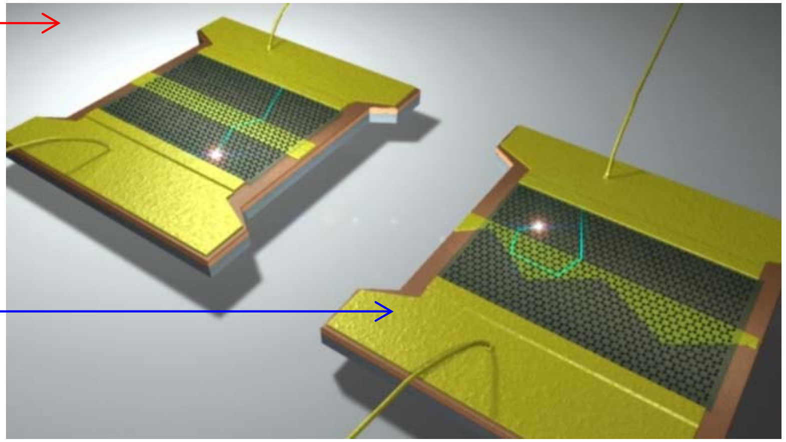
Q. Wilmart et al. / 2D Materials 1 (2014) 011006

Klein tunneling transistor (modelling)

Scattering model and NGEF simulations



Klein Tunneling conductance

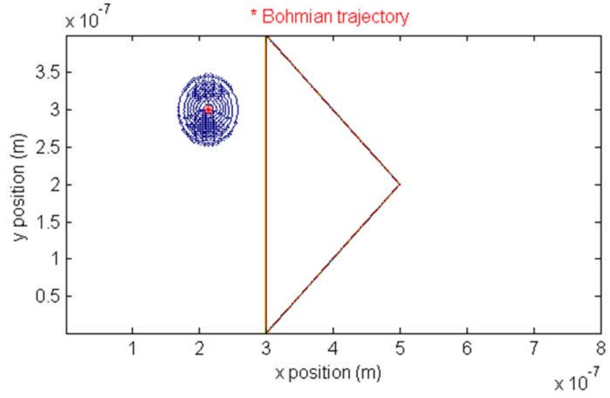


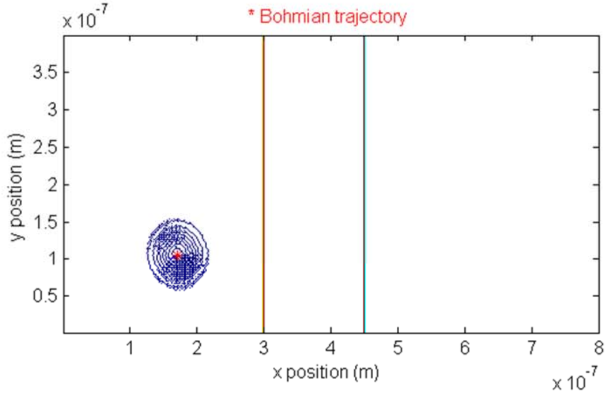
Diffraction limited nano KT-FETs device

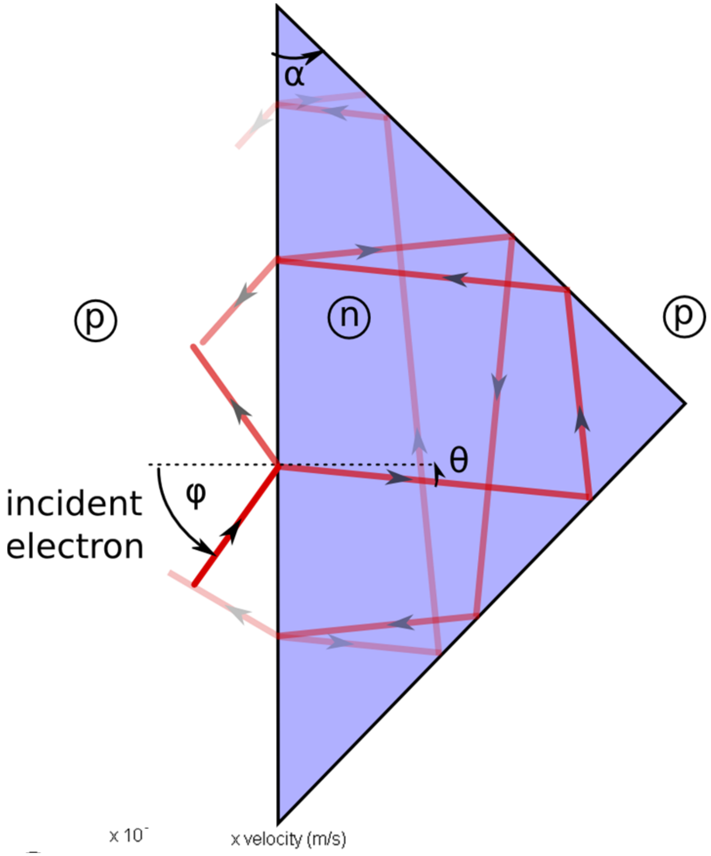
Q. Wilmart et al. / 2D Materials 1 (2014) 011006

Wave packet approach

(poster Enrique Colomes)

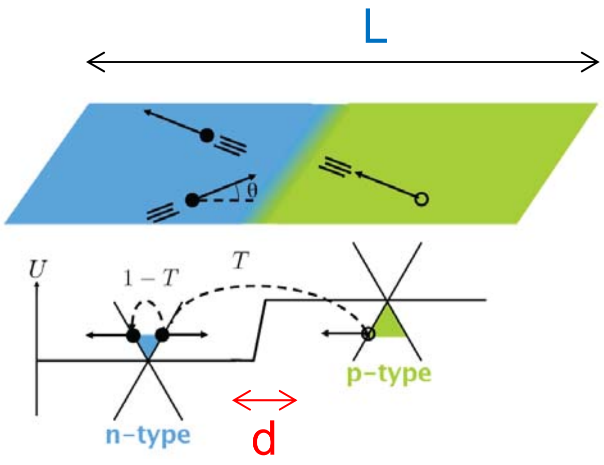






Courtesy of D. Jimenez (UAB)

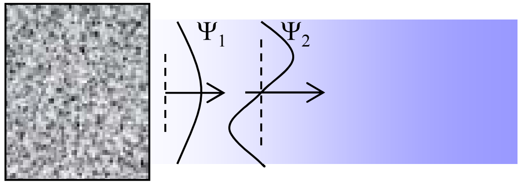
Requirements for DFO



- Widely tunable index $n=-k_n/k_p$
- Incoherent DFO at room temperature
- Ballistic transport $L \ll l_B, l_{e-e}$
- Geometrical optics $L \gg \lambda_F$
- Sharp junctions $d/\lambda_F \leq 1$
- Homogeneous medium $\delta k_F \ll k_F$

Getting ballistic graphene

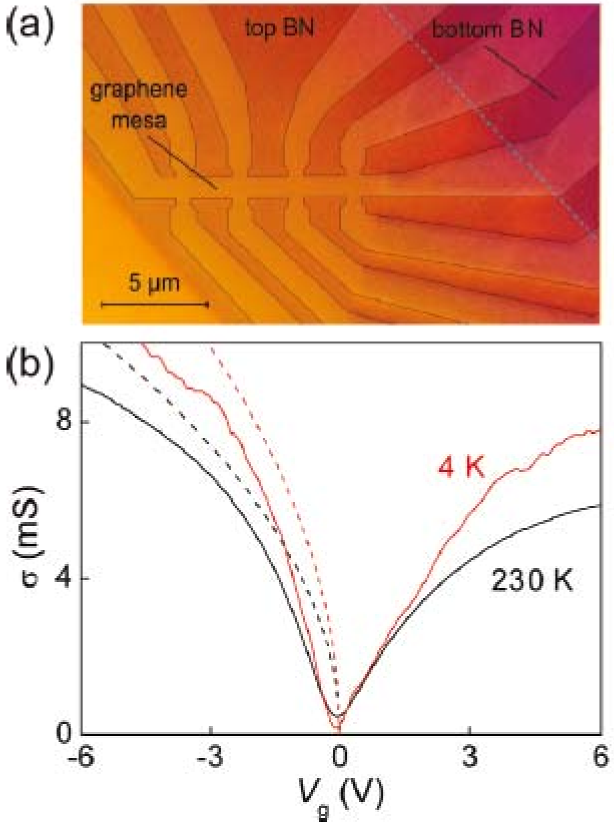
Landauer-Büttiker



$$G_L = \frac{4e^2}{h}\frac{k_F W}{\pi} = \frac{56}{6450} \times \sqrt{\tilde{n}}$$

- $\tilde{n}$=n/10^{12} cm^{-2}

GBN heterostructure



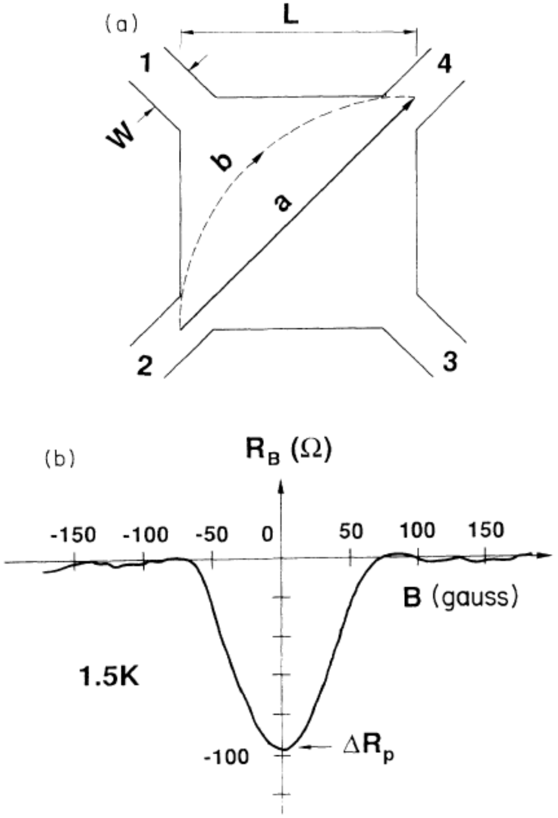
A.S. Mayorov et al. / Nano Lett. 11 (2011) 2396

Bend resistance criterion (GaAs)

bend resistance

ballistic length

$$R_B = \frac{1}{N^2}\frac{h}{e^2}\left[\frac{D_{left}+D_{right}}{2} - D_{direct}\right] \quad ; \quad \sqrt{2}LR_B = \frac{\sqrt{\pi n}}{2}\frac{h}{e^2}\, exp(-\sqrt{2}L/l_B)$$



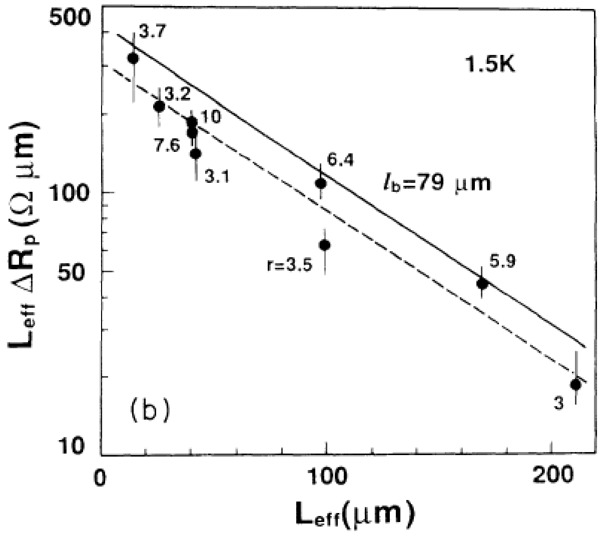


FIG. 2. (a) Plots of $L_{\rm eff}\Delta R_p$ vs $L_{\rm eff}$ for devices with various L and r ($=L/W$) values. The solid line results from the calculation of Eq. (5) with $l_b=39$ μm and $n=3.0\times10^{11}$ cm^{-2}. The $L_{\rm eff}\Delta R_p$ plots follow the slope shown by the dashed line, which represents exp($-L_{\rm eff}/l_b$) with $l_b=39$ μm. (b) Similar plots for a different series of devices fabricated from a wafer that has $\mu=7.8\times10^6$ cm^2/V s and $n=2.8\times10^{11}$ cm^{-2}.

S. Tarucha et al. / Phys. Rev. B 45 (1992) 13465

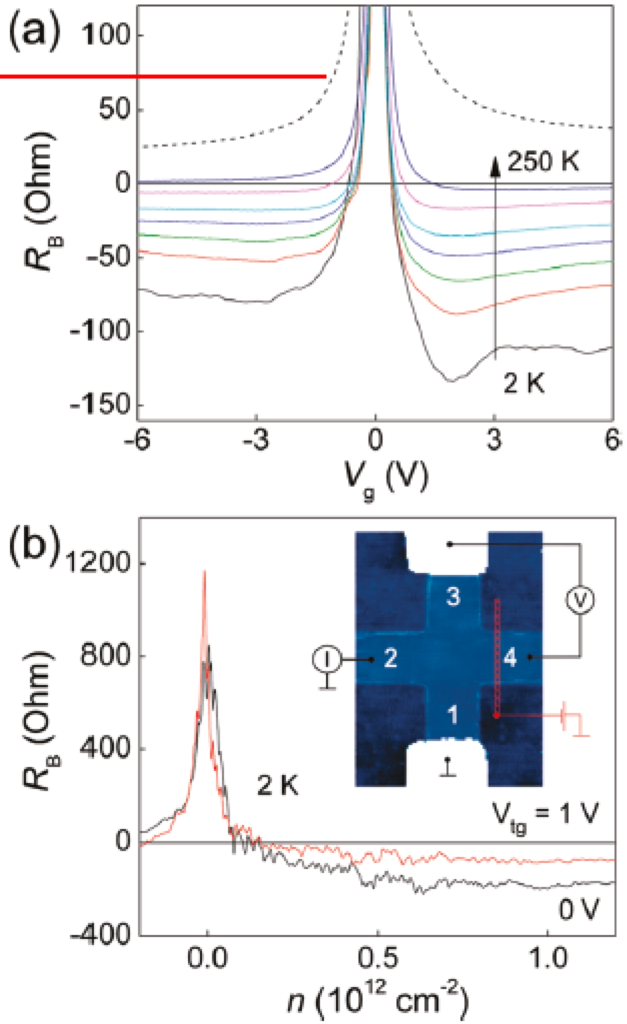
Bend resistance criterion (Graphene)

$$R_B = \frac{\ln(2)}{\pi\sigma}$$ (van der Pauw mobility)

- R_B smaller than diffusive limit
- Negative R_B at high doping
- Temperature dependence (phonons)

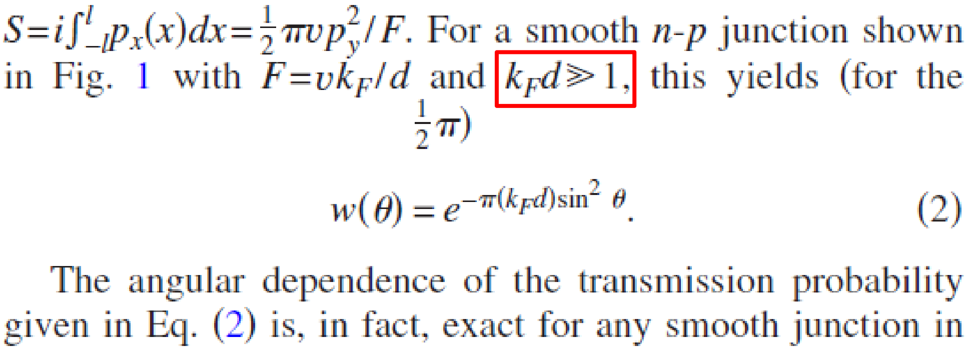
$$l_{mfp} = \frac{h}{2e} \times \mu \times \sqrt{\frac{n}{\pi}} = \mu \times \frac{\varepsilon_F/e}{v_F}$$

- L_{mfp}=1μm @ $\mu=10^5$ cm^2/V/s, n=10^{12} cm^{-2}
- Ballistics requires high mobility and density!



A.S. Mayorov et al. / Nano Lett. 11 (2011) 2396

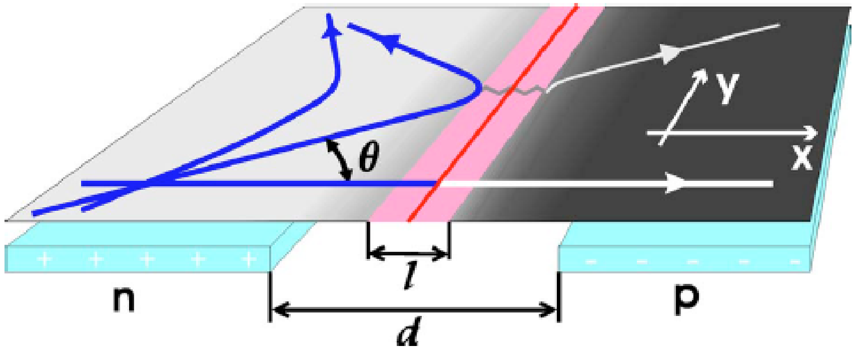
“smooth” p-n junctions



$S=i\int_{-l}^{l}p_x(x)dx=\frac{1}{2}\pi v p_y^2/F$. For a smooth n-p junction shown in Fig. 1 with $F=vk_F/d$ and $\boxed{k_F d \gg 1,}$ this yields (for the $\frac{1}{2}\pi$)

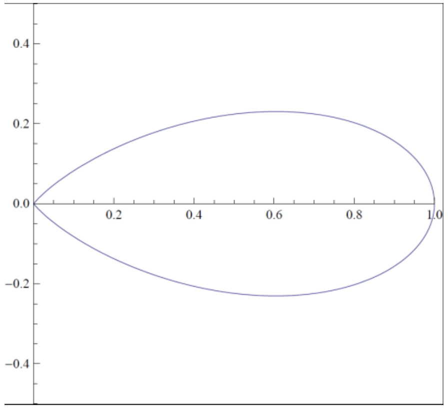
$$w(\theta)=e^{-\pi(k_F d)\sin^2\theta}. \qquad (2)$$

The angular dependence of the transmission probability given in Eq. (2) is, in fact, exact for any smooth junction in

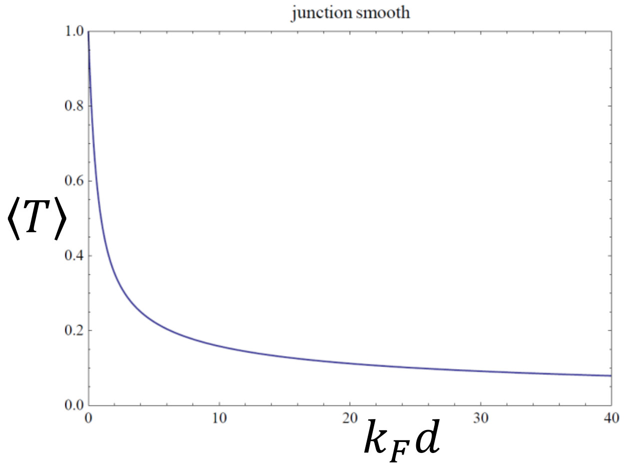


$$\boxed{G_L = \frac{4e^2}{h}\frac{k_F W}{\pi}\langle T\rangle}$$

transparency is too low for DFO !



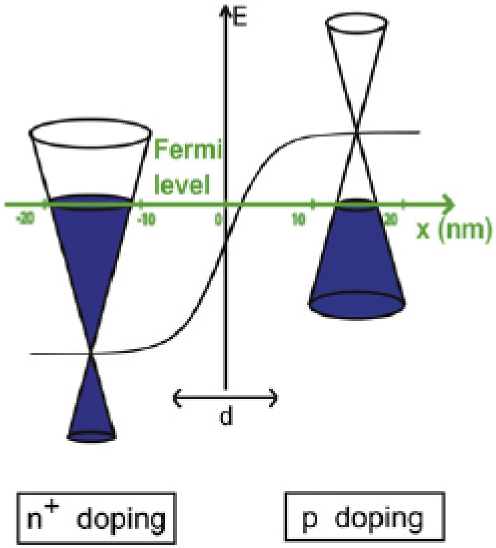
$$\boxed{\langle T\rangle = \int_0^1 exp[-\pi x^2(k_F d)]dx}$$



V.V. Cheianov and V.I. Falko / Phys. Rev. B. 74 (2006) 041403 (R)

“sharp” p-n junctions

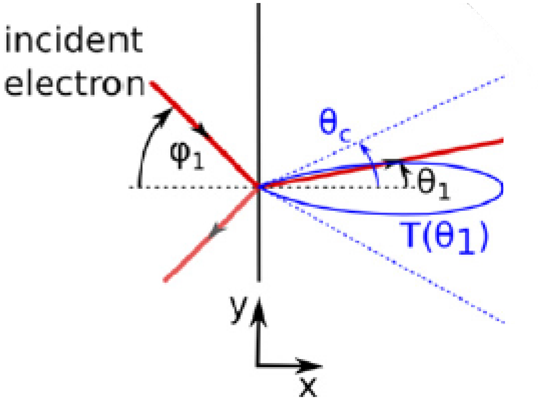
Fermi-function-like potential step



$$k_F(x) = k_n + \frac{k_n - k_p}{e^{-x/w} + 1}$$

Anomalous Snell-Descartes refraction

$$\sin\varphi = -\left(k_n/k_p\right)\sin\theta$$



Fresnel-like relations

$$T(\varphi) = 1 - \frac{\sinh(\pi w k^{+-})\sinh(\pi w k^{-+})}{\sinh(\pi w k^{++})\sinh(\pi w k^{--})}$$

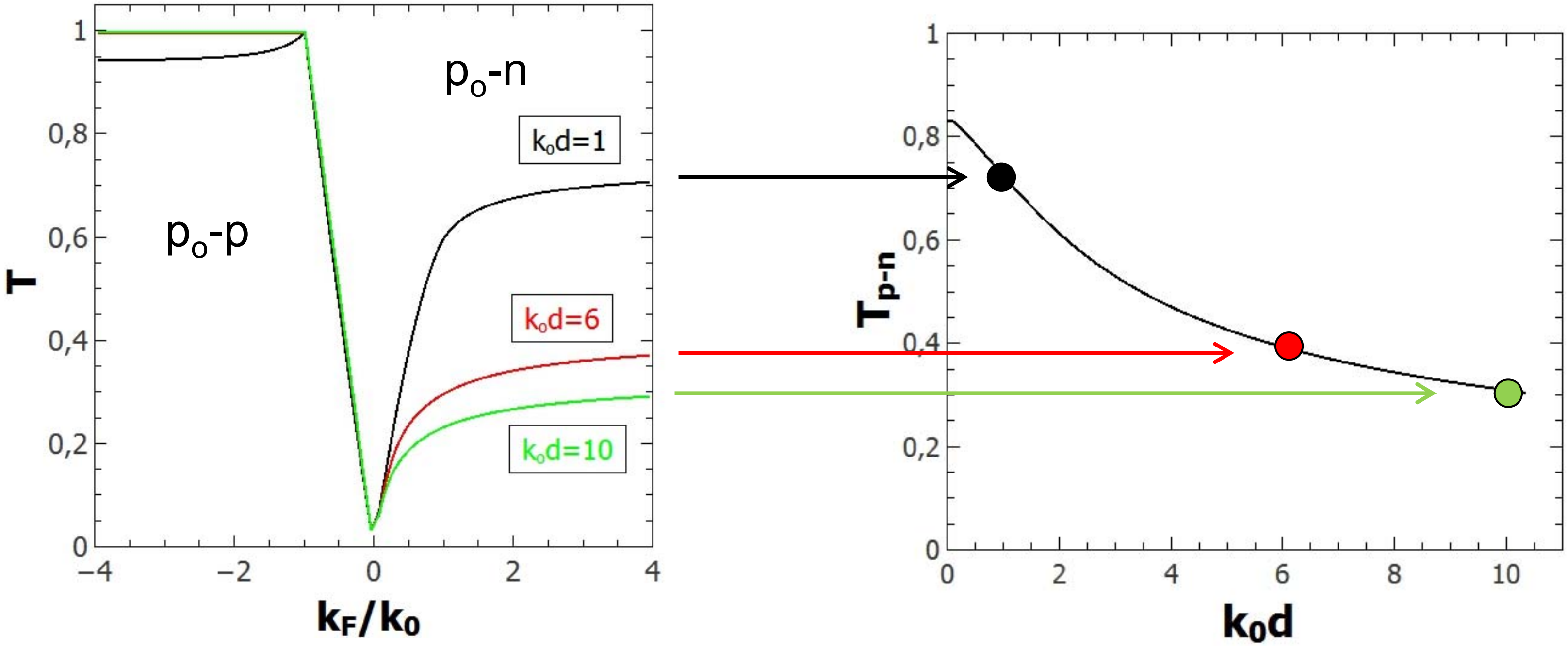
$$k^{\alpha\beta} = k_p(1 + \alpha\cos\varphi) + k_n(1 + \beta\cos\theta)$$

J. Cayssol, B. Huard et al. / Phys. Rev. B. 74 (2006) 041403 (R)
Q. Wilmart et al. / 2D Materials 1 (2014) 011006

Transmission of a “sharp” p-n junction

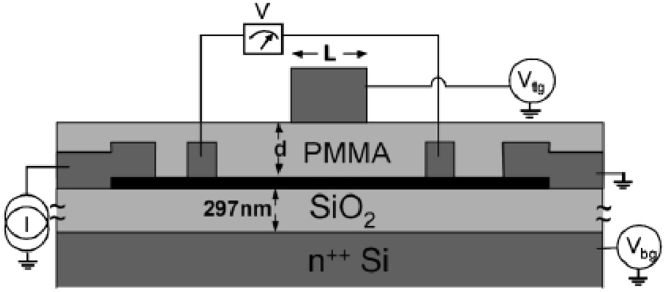
as function of channel doping

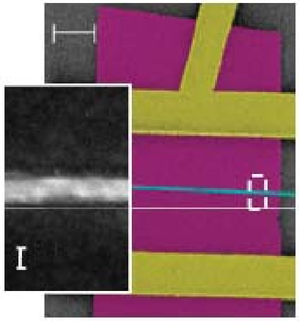
as function of junction length (p-n)

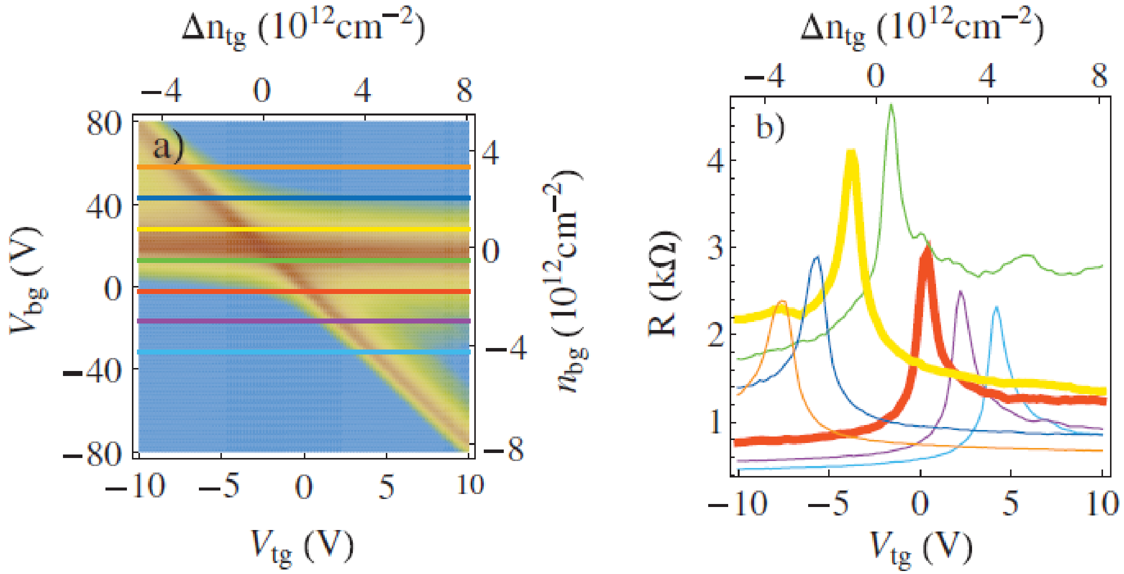


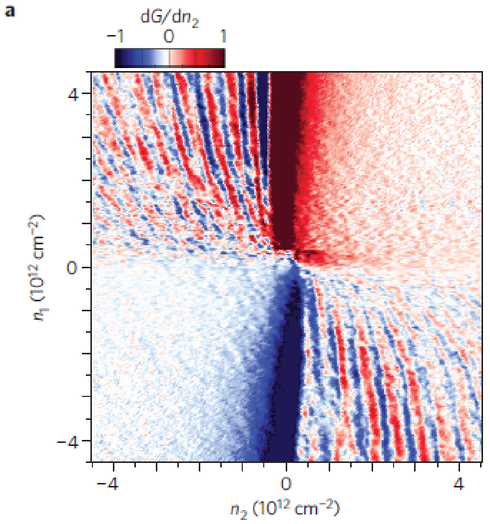
J. Cayssol et al. / Phys. Rev. B. 74 (2006) 041403 (R)
Q. Wilmart et al. / 2D Materials 1 (2014) 011006

Experiments with top + bottom gates





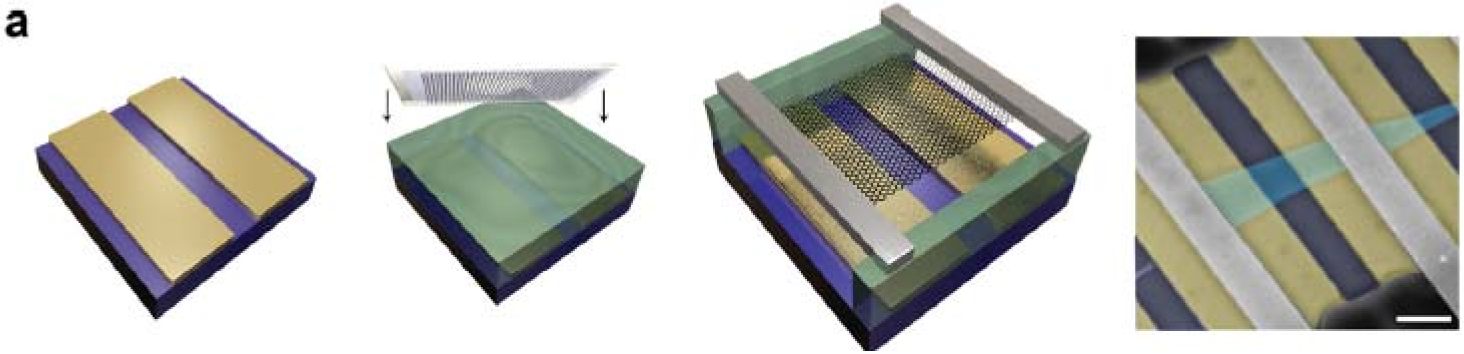


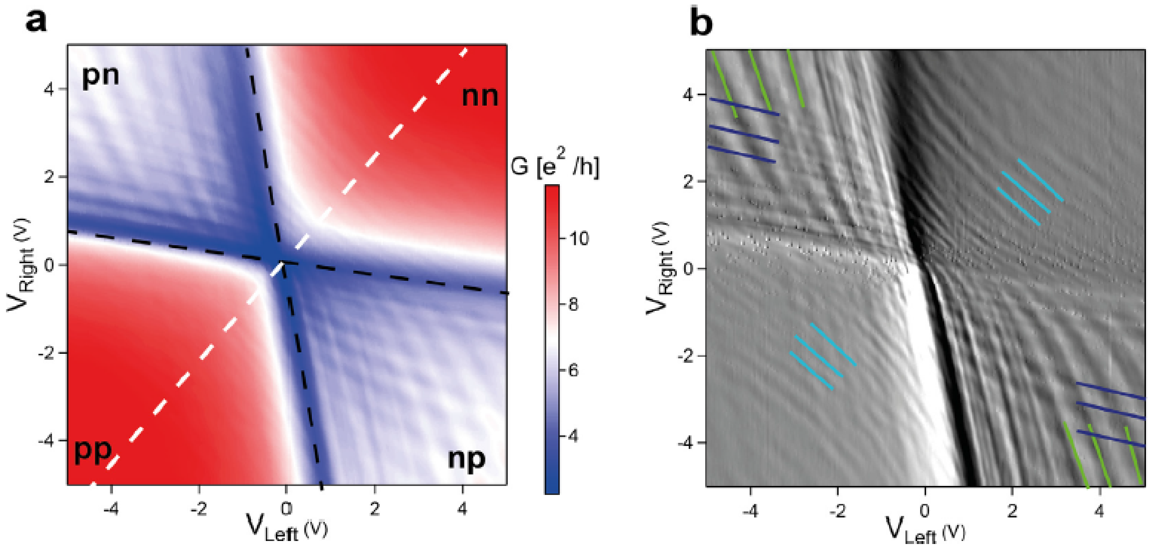


Huard-Stander et al. / Phys. Rev. Lett. 98 (2007) 236803; Phys. Rev. Lett. 102 (2009) 026807*;*
A. Young and P. Kim al. / Nat. Phys. XX (2009) YYYYYYY

Suspended graphene with (remote) back gates

Suspended G : Simon Zihlmann and Bàlint Fülöp posters !!

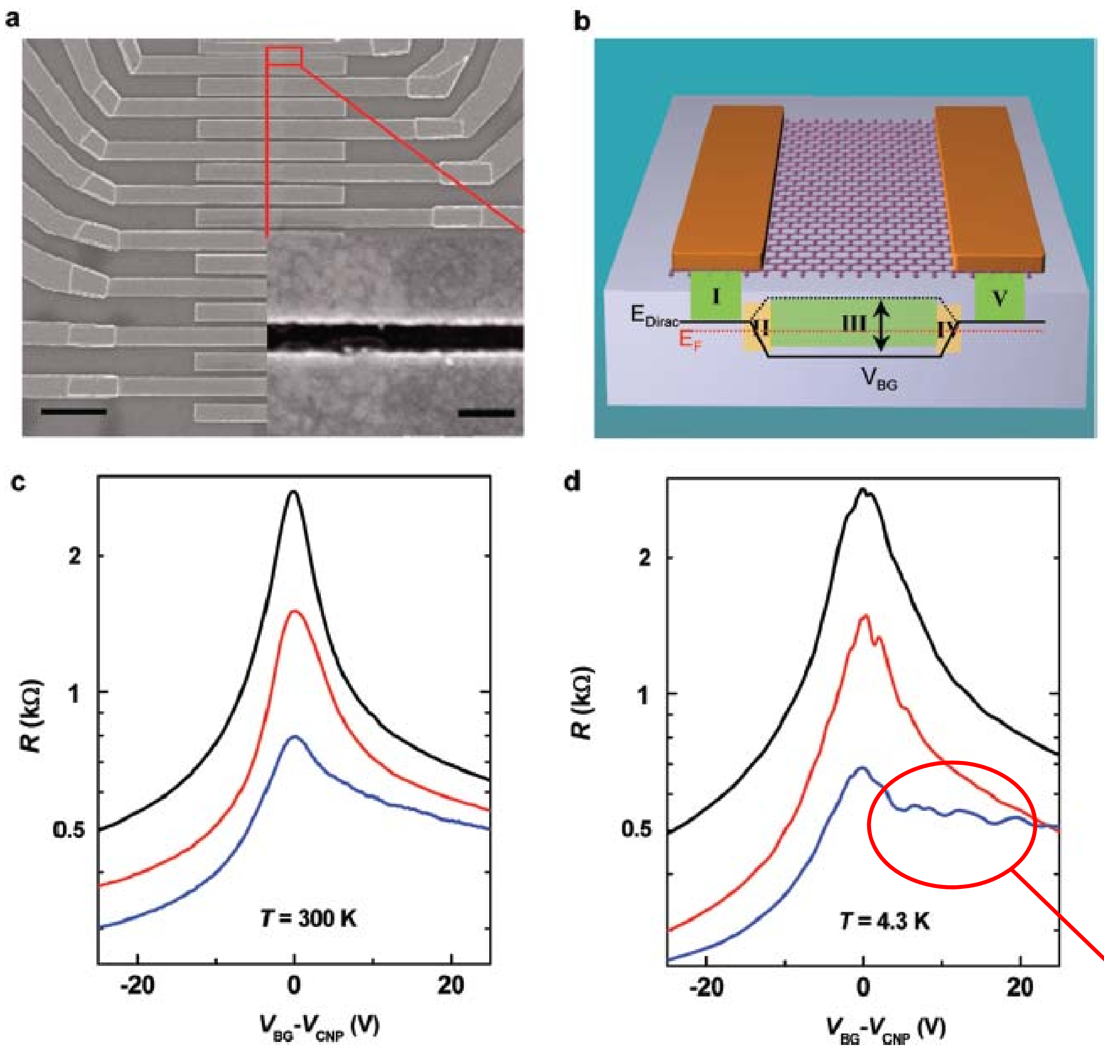




Fabry-Pérot oscillations, Guiding effects, Quantum Hall effect, Snakes states, ...

A.L. Grushina et al. / Appl. Phys. Lett. 102 (2013) 223102; Maurand et al./ Carbon 79 (2014) 486

Sharp contact junctions



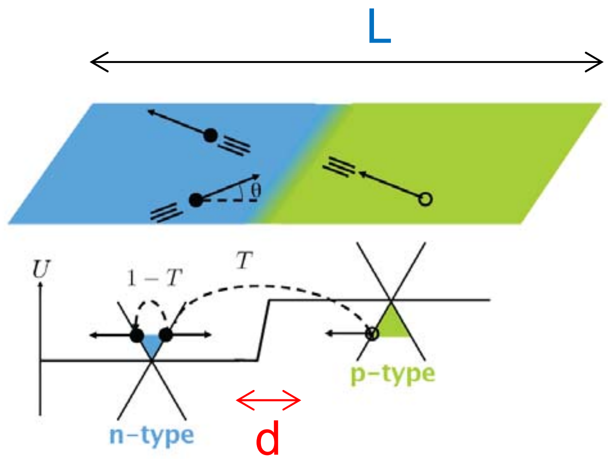
L=500 nm

L=170 nm

L=50 nm

weak Fabry-Pérot oscillations

Y. Wu et al. / Nano Letters 12(2012) 1417

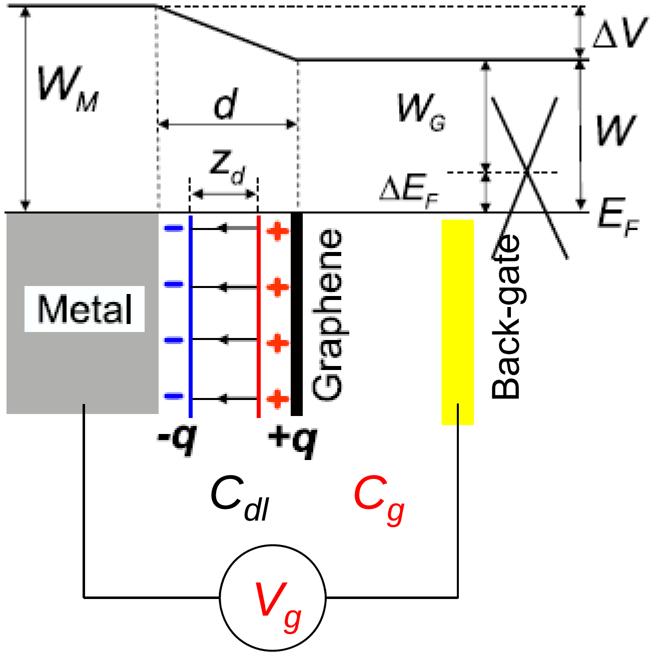


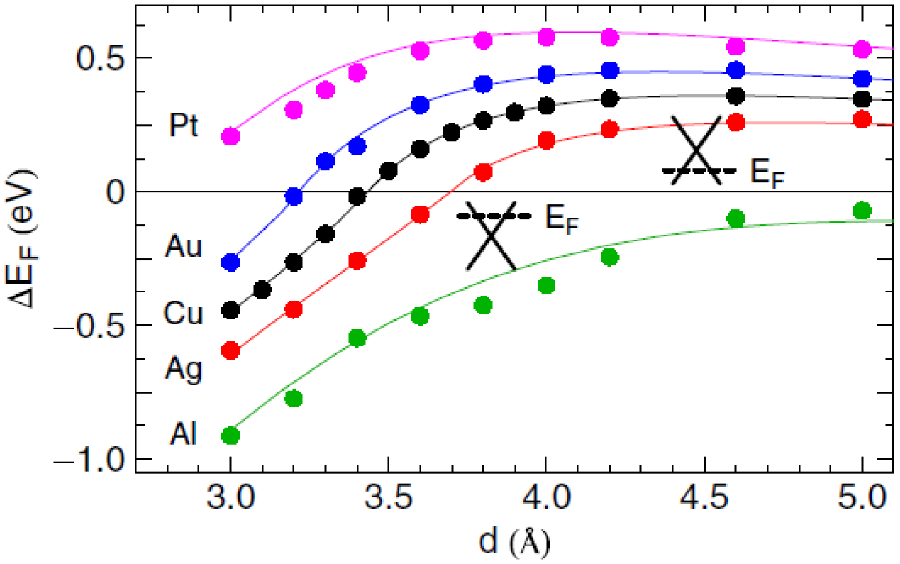
Can we use contact junctions for
Dirac Fermion optics ?

Yes, provided that one can tune contact doping

Field-effect control of metallic doping

contact : $\mu_G - eV_G = \mu_m - eV_m \Rightarrow \mu_G$ is gate-tunable (2DM only !!)





$$\mu_G = \frac{\varepsilon_w \varepsilon_c}{|\varepsilon_w|} \times \left(1 + \sqrt{1 + 4\,|\varepsilon_w|/\varepsilon_c}\right)$$

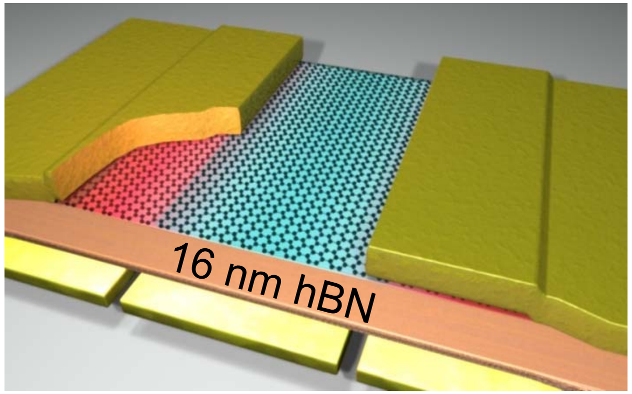
with

$$\varepsilon_w = \Delta W - \frac{C_g}{C_g + C_{dl}}\, eV_g \quad ; \quad \varepsilon_c = \pi \hbar^2 v_F{}^2 \left(C_g + C_{dl}\right)/e^2$$

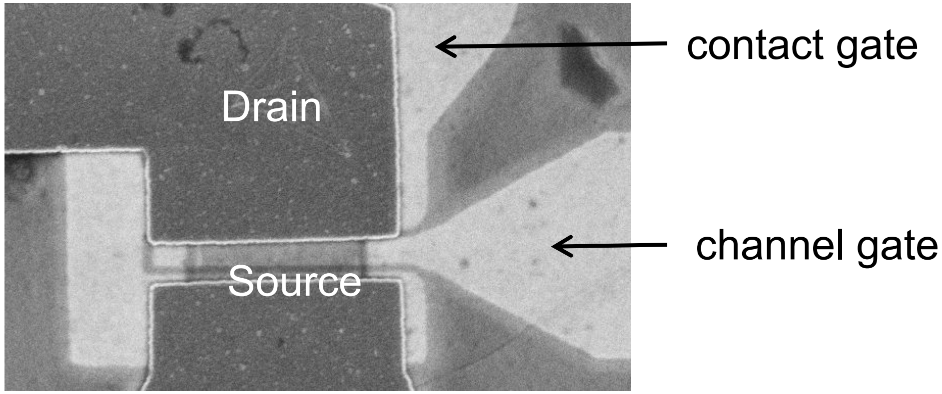
G. Giovanetti et al. / Phys. Rev. Lett. 1001 (2008) 026803

contact junctions with gated contacts

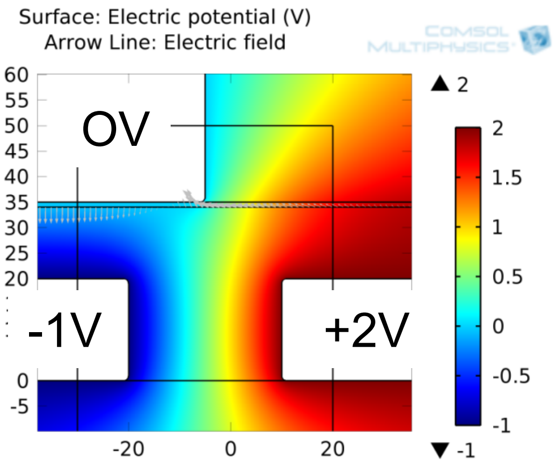
Artist view



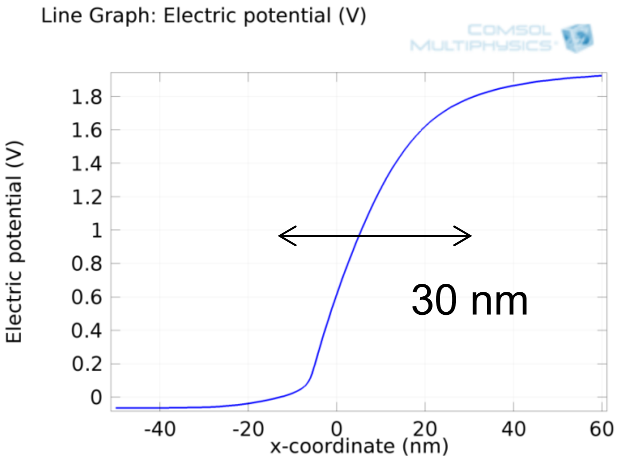
Sample : local back gates with 30 nm gaps



Numerical simulation of 2D potential

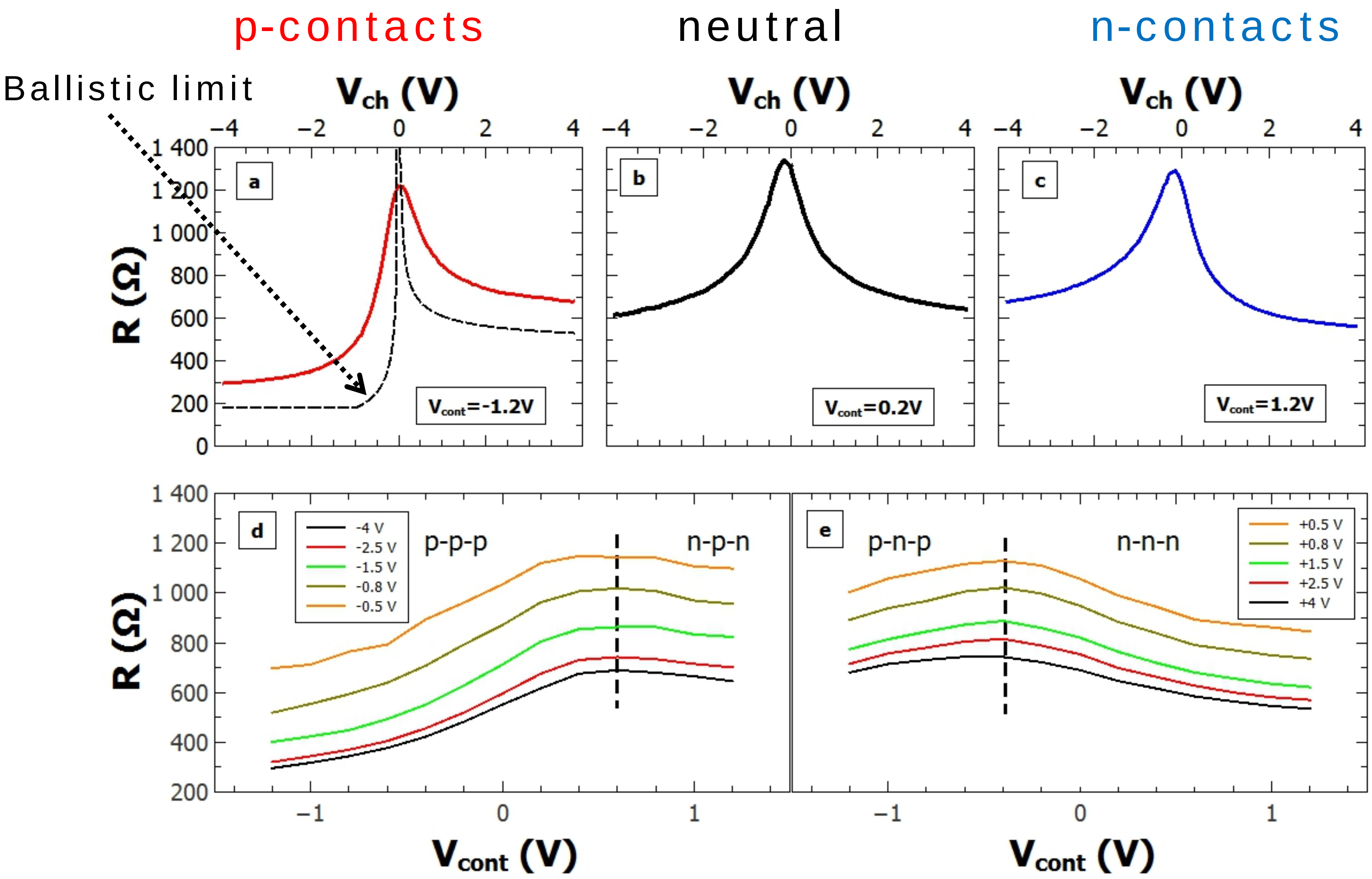


Calculated potential step at the contact



Q. Wilmart thesis

In graphene, contact is also tunable

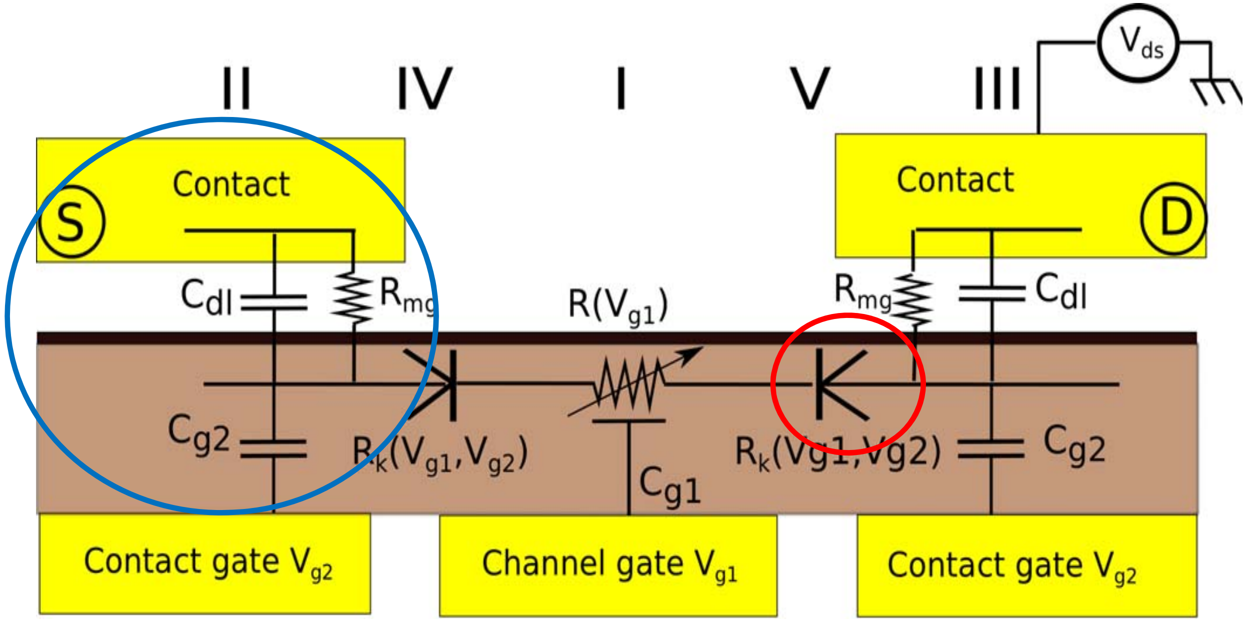


Q. Wilmart thesis

Modelling tunable contact junctions

Electrostatic model of the metallic contact
(Giovanni et al, PRL 2008)
(*Xia et al, nature 2011*)

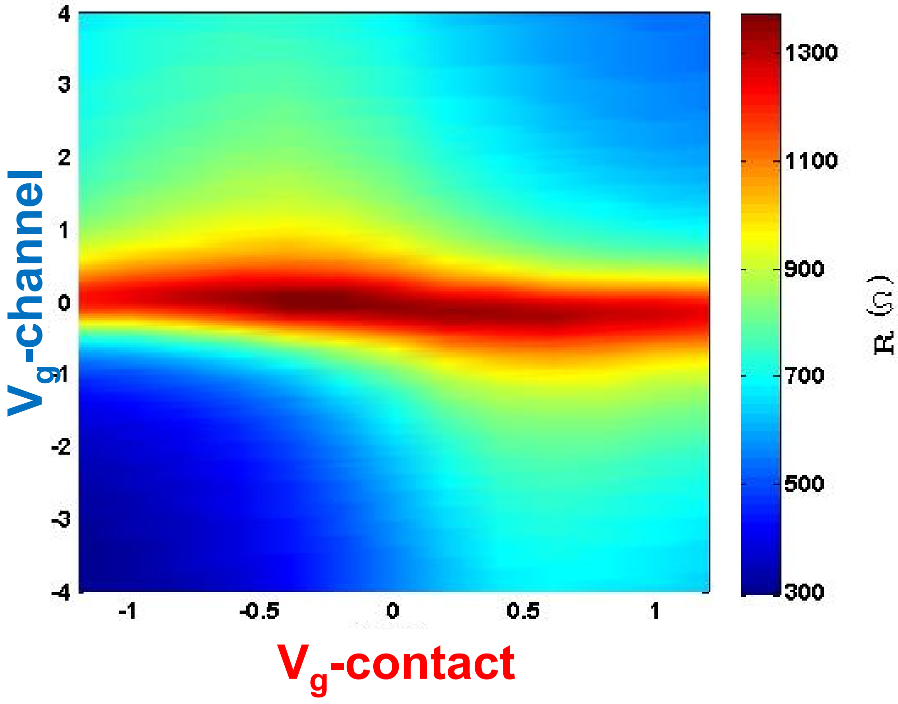
Ballistic junction model
(*Cayssol et al, PRB 2009)*
(Wilmart et al., 2DM 2014)



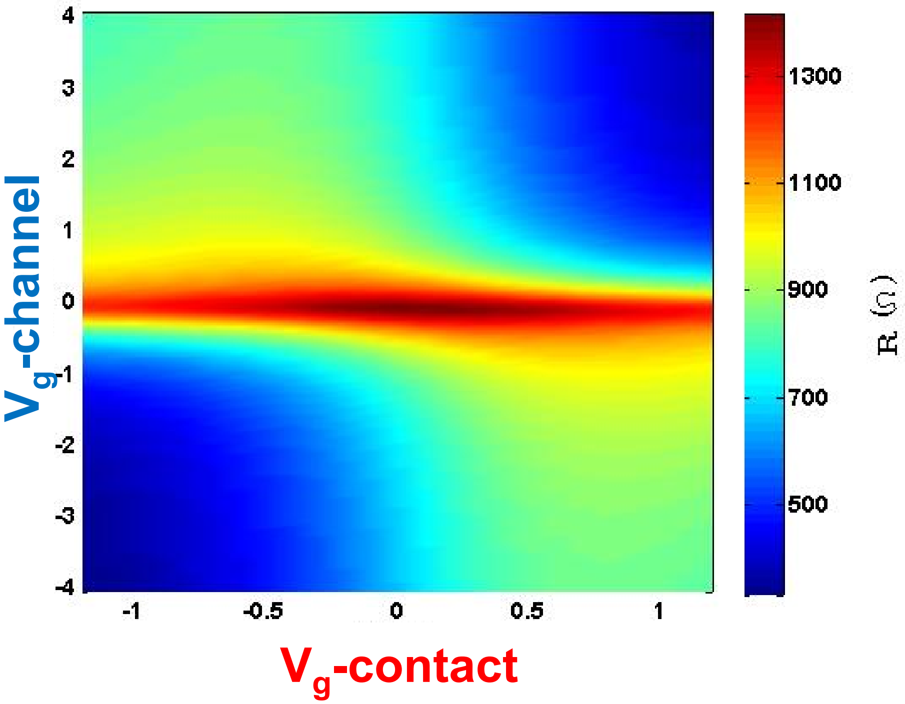
Q. Wilmart thesis

Fitted parameters

Measured



Simulated



Fixed parameters : junction length (30nm) , hBN -thickness (16 nm)

Fitted parameters : μ = 6000 cm^2/V/s, Pd doping : 50meV, double layer thickness (2nm), metal-graphene resistance (~100 Ohm.μm)

Q. Wilmart thesis

Gated-contacts can be useful

- Use contact junctions for DFO
- Contact gated transistor (below)
- p-n junctions for photo-detection/mixing
- Nano-plasmonics, etc…

L2 : Ballistic graphene devices

Benefits of ballistics in conventionnal FETs ?

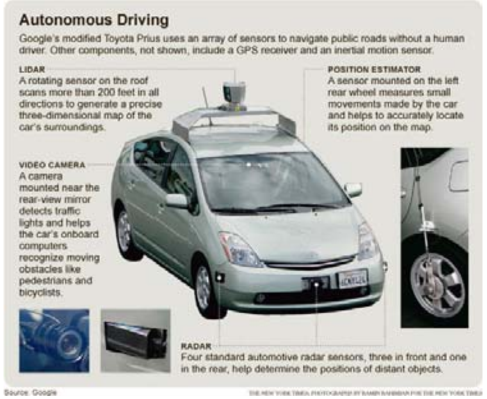
- High-mobility G-FETs
- Contact-gated transistor

High-frequency field effect transistors

Radars for aircrafts

600 GHz

for vehicules



Autonomous Driving

Google's modified Toyota Prius uses an array of sensors to navigate public roads without a human driver. Other components, not shown, include a GPS receiver and an inertial motion sensor.

LIDAR
A rotating sensor on the roof scans more than 200 feet in all directions to generate a precise three-dimensional map of the car's surroundings.

POSITION ESTIMATOR
A sensor mounted on the left rear wheel measures small movements made by the car and helps to accurately locate its position on the map.

VIDEO CAMERA
A camera mounted near the rear-view mirror detects traffic lights and helps the car's onboard computers recognize moving obstacles like pedestrians and bicyclists.

RADAR
Four standard automotive radar sensors, three in front and one in the rear, help determine the positions of distant objects.

Source: Google

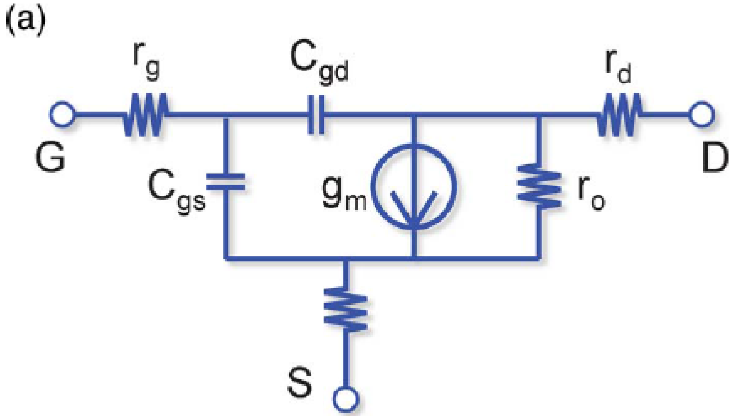
70GHz

THz imaging

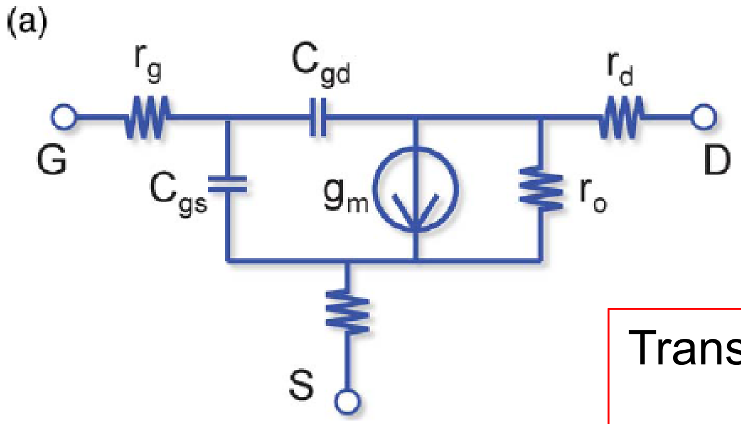
50-500 GHz

LNAs for telecom.

e.g. >90 GHz



Glossary of RF transistors



Transconductance : $g_m = \partial I_{ds}/\partial V_g$

Differential conductance : $g_{ds} = \partial I_{ds}/\partial V_{ds} \approx 1/r_o$

Voltage gain : $A = g_m/g_{ds} \approx r_o g_m$

Current gain : $H = 1 - 1j\omega_T/\omega$

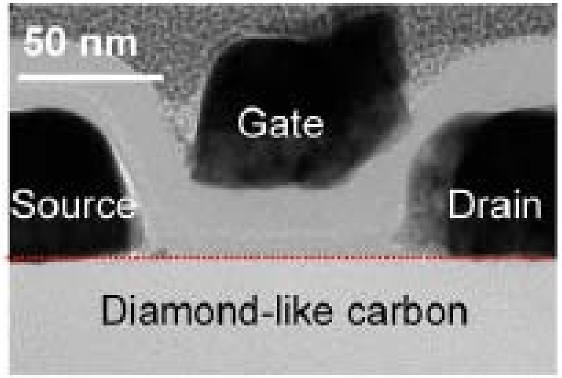
Transit frequency : $f_T = g_m/2\pi C_g$

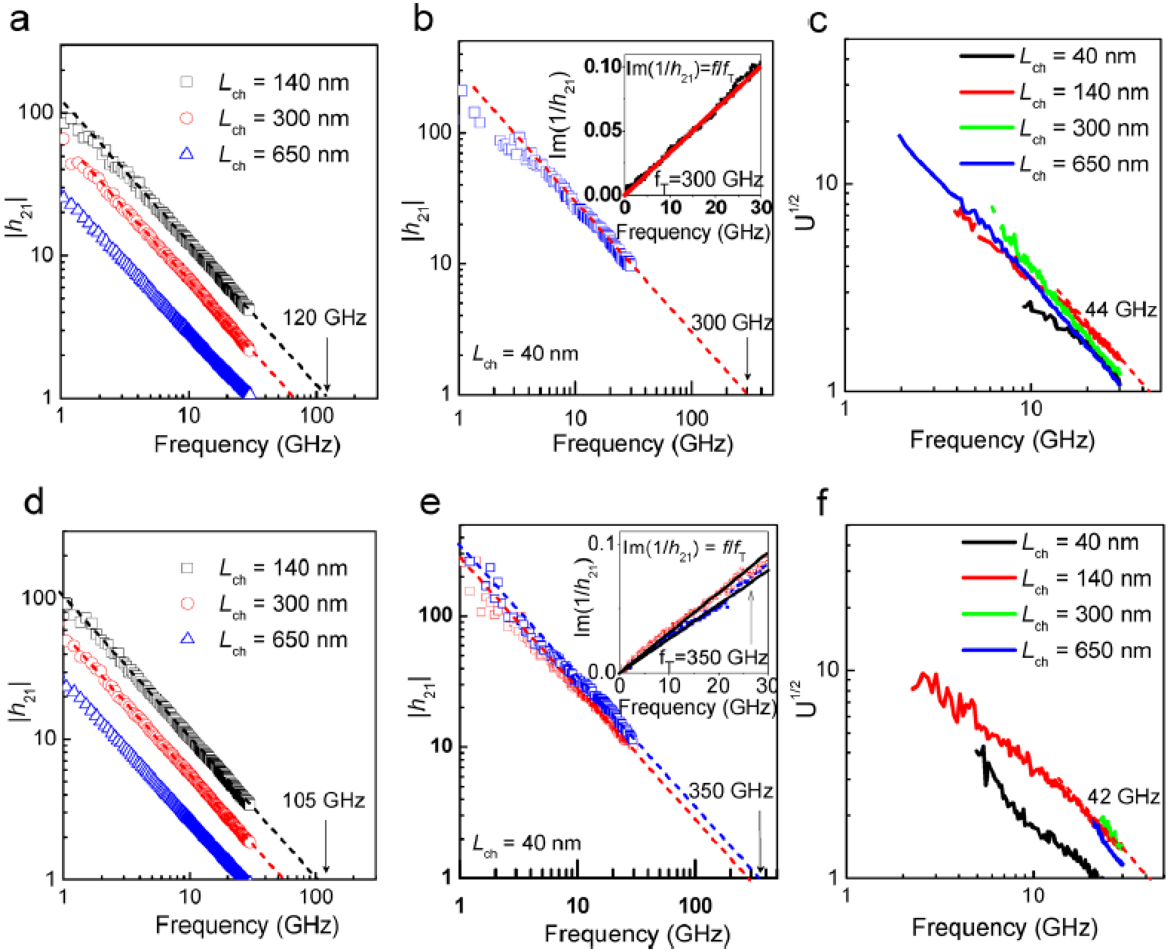
Power gain : $\mathrm{U} \approx (\omega_{max}/\omega)^2$

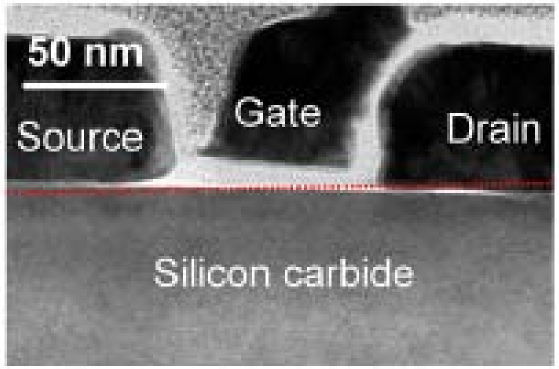
Max oscillation frequency : $f_{max} \sim \sqrt{A} \times f_T/2$

Power cutoff frequency ?

In conventional G-FETs : $f_{max} \approx const. \ll f_T = \frac{g_m}{C_g} \propto \frac{1}{L}$



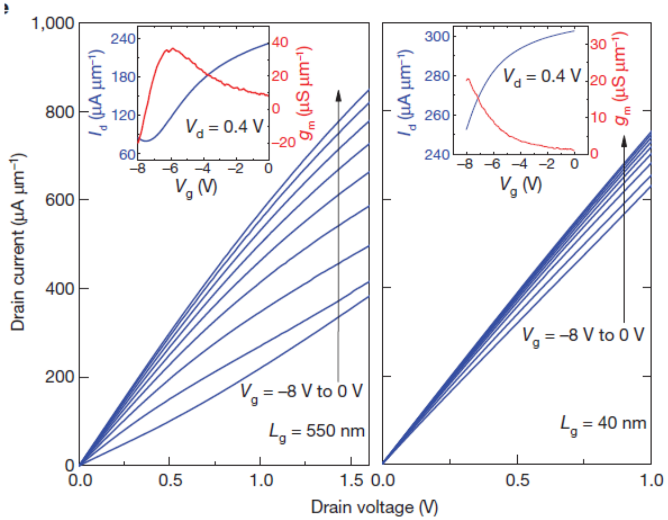


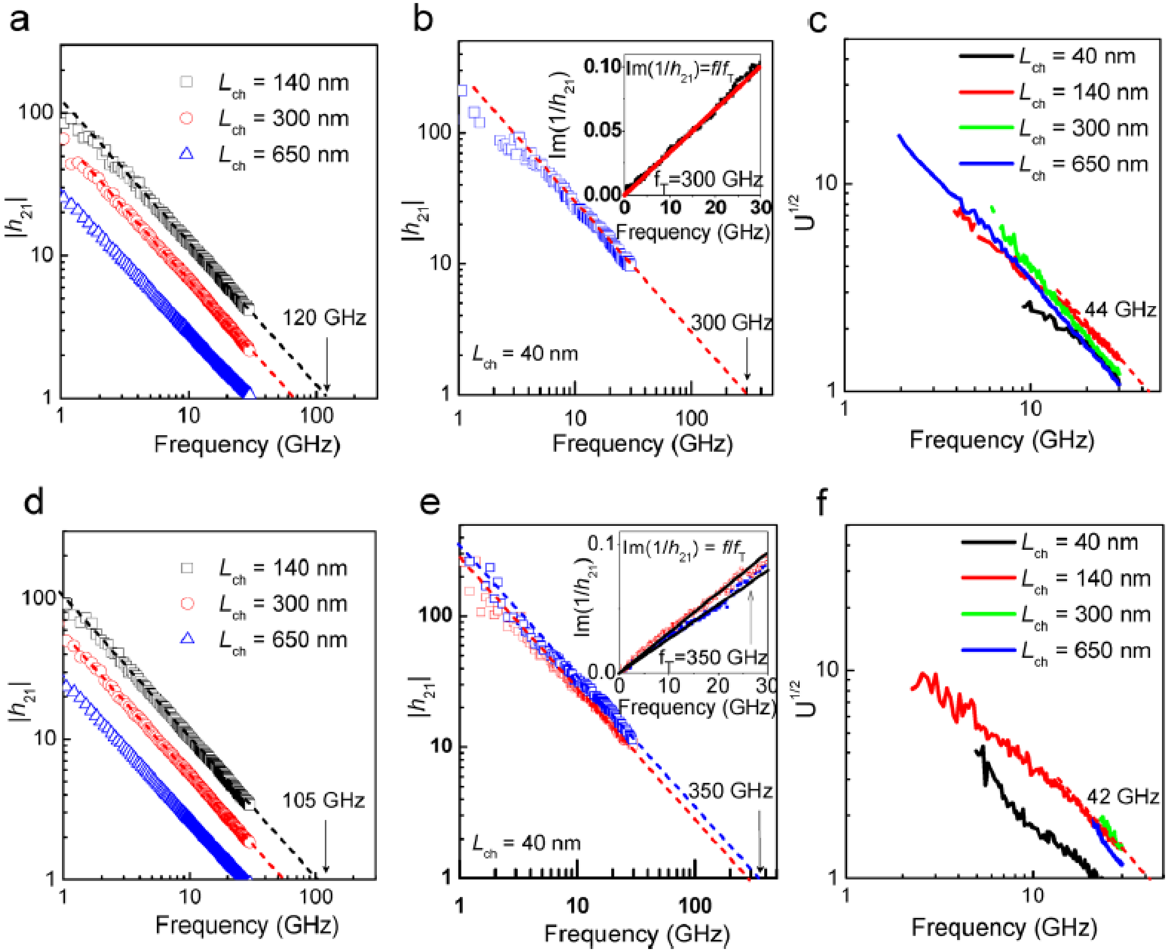


Y. Wu et al. / Nano Letters 12 (2012) 3062

power cutoff frequency ?

Problem is the lack of current saturation





$$f_{max} \sim \sqrt{A} \times f_T/2$$

$$A \sim \frac{g_m}{g_{ds}} \le 1$$

Y. Wu et al. / Nano Letters 12 (2012) 3062

Phonon saturation in high-mobility graphene

Solution : graphene on BN (one more time !)

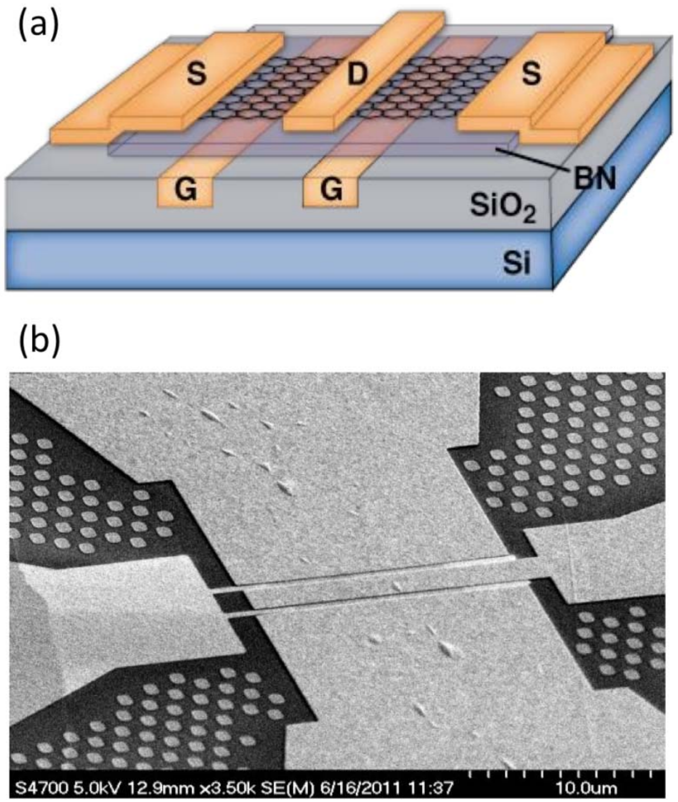
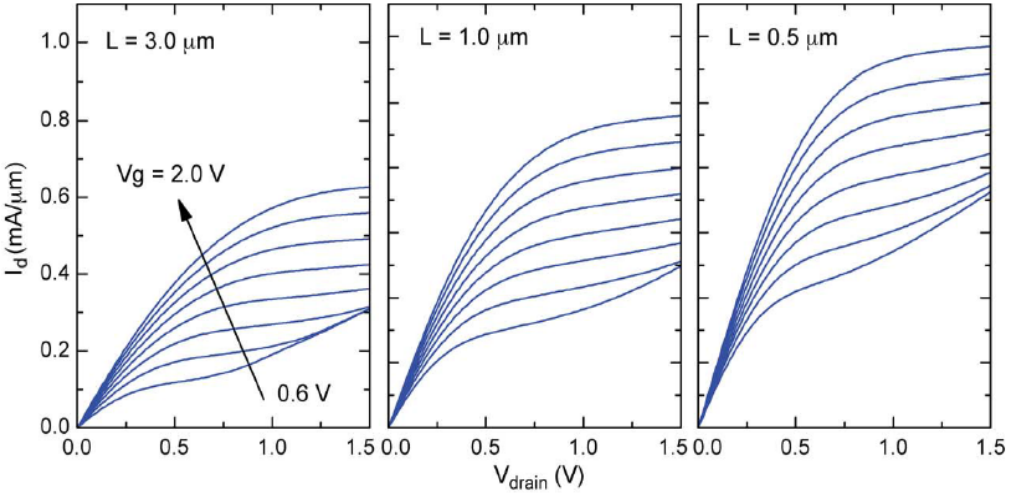
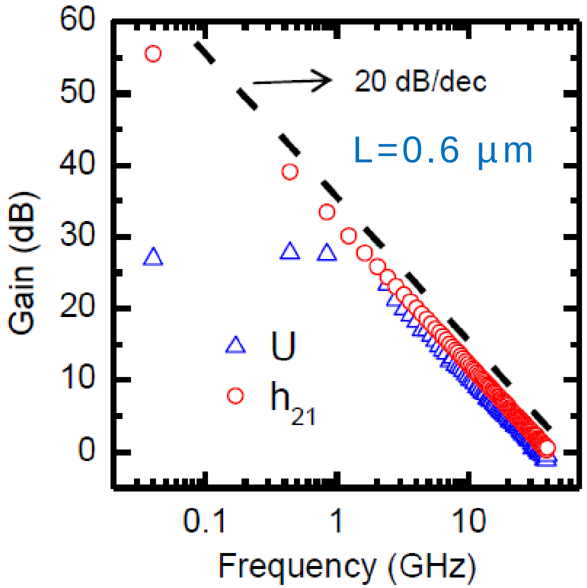


Figure 1. GFET device structure. (a) Schematic illustration of the back-gated GFET device. (b) SEM micrograph of a completed structure.



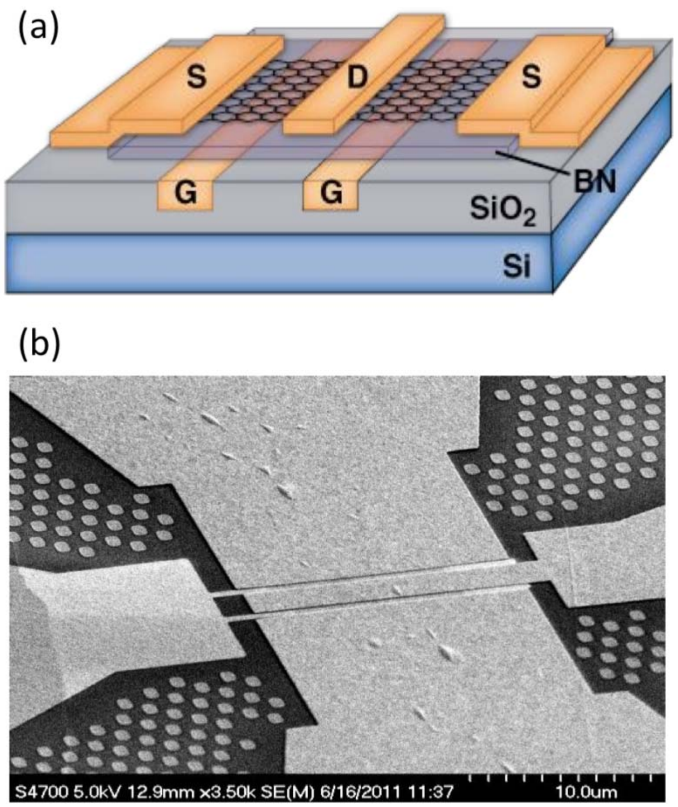


$f_{max} \sim f_T$ ‼

I. Meric et al. / IEEE (2011)

Phonon saturation in ballistic graphene

Ballistics enhances (differential) resistance !!



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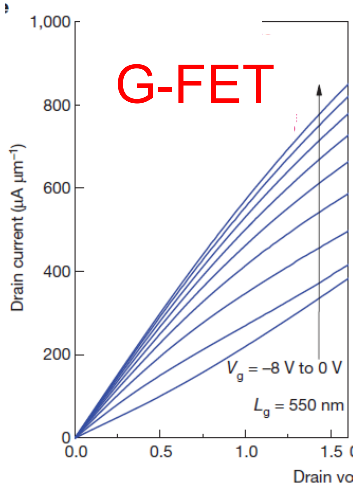
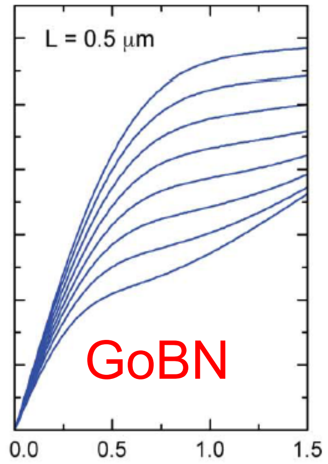
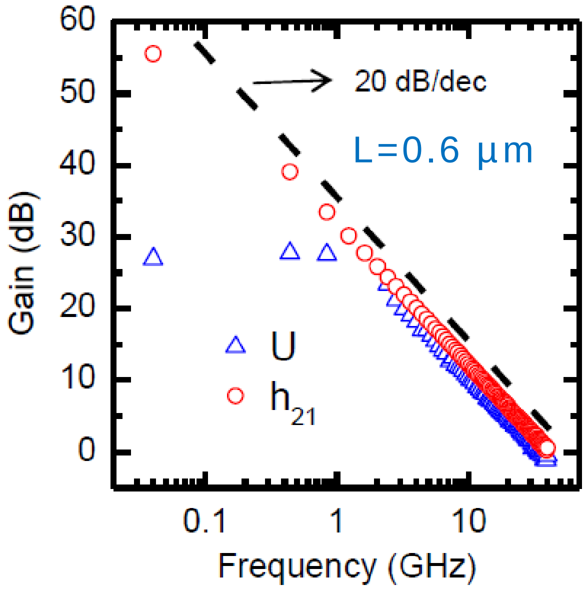


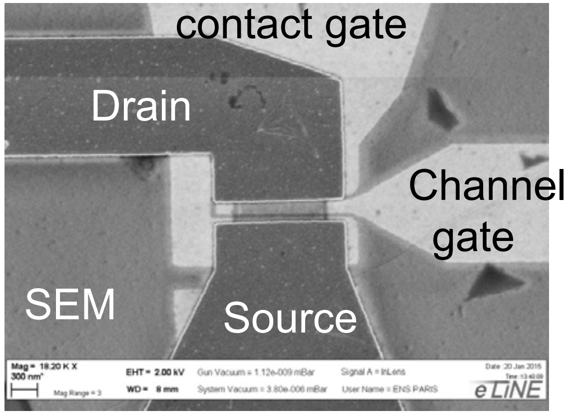


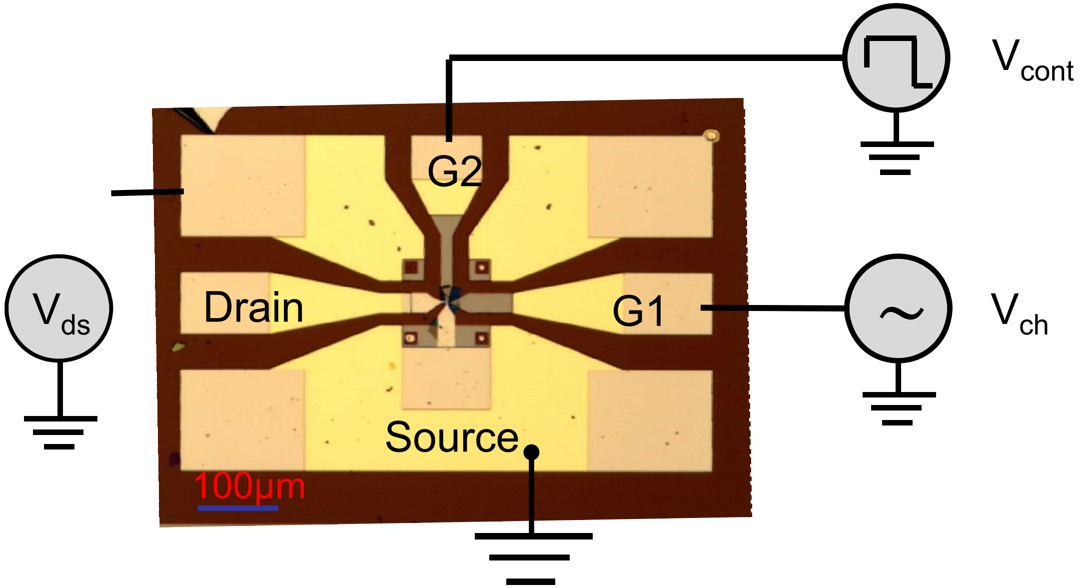


$f_{max} \sim f_T$!!

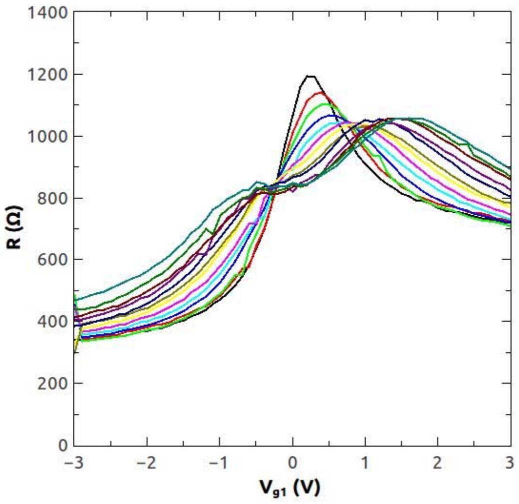
I. Meric et al. / IEEE (2011)

The contact gated RF transistor

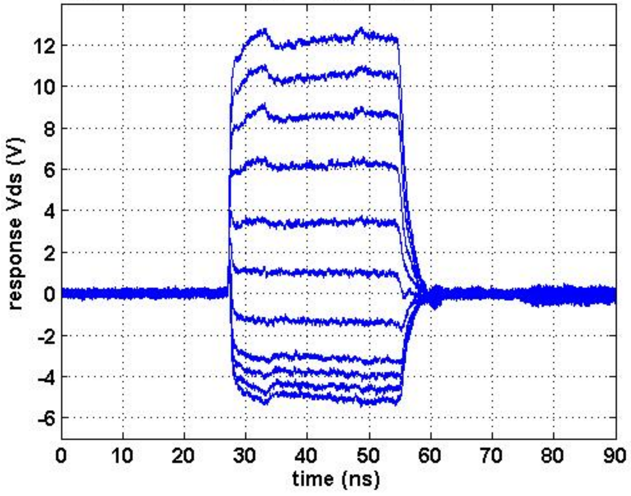




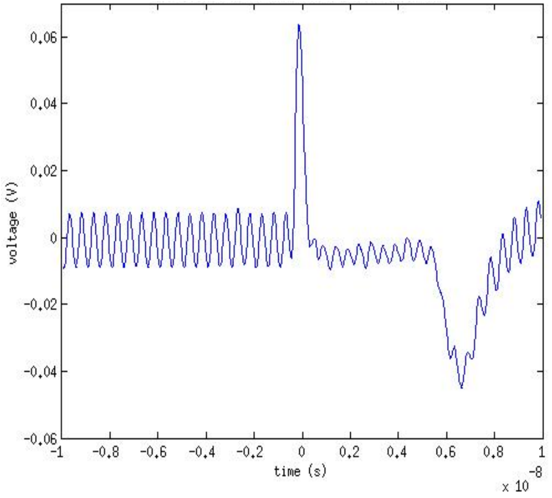
Differential resistance



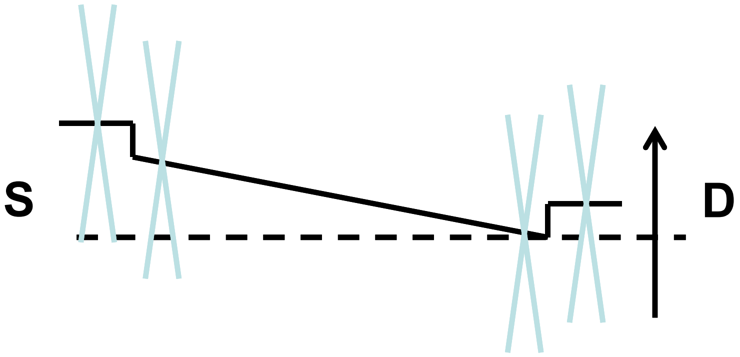
Pulsed contact gating

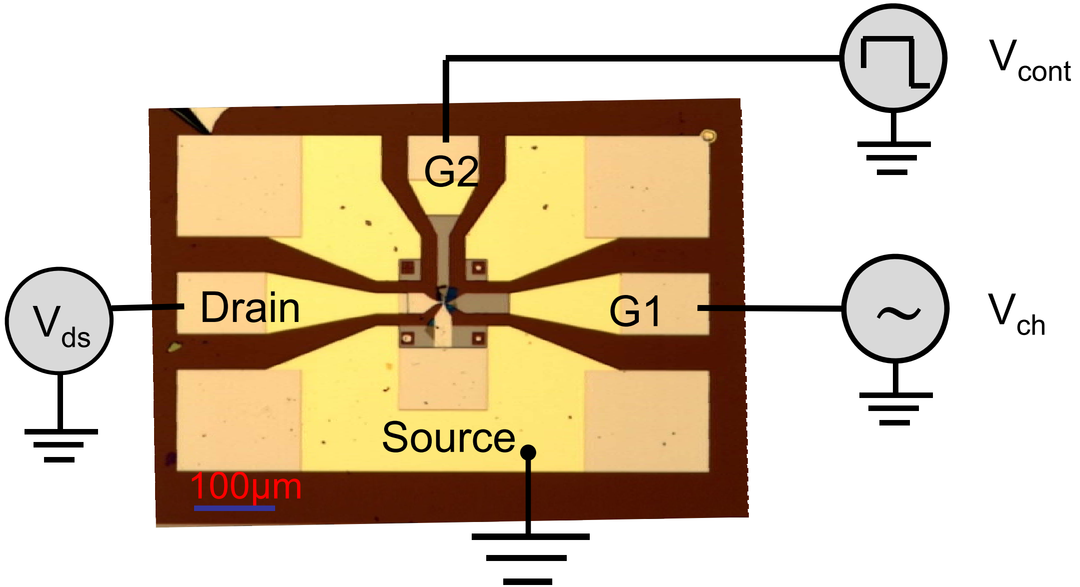


RF-gain switching

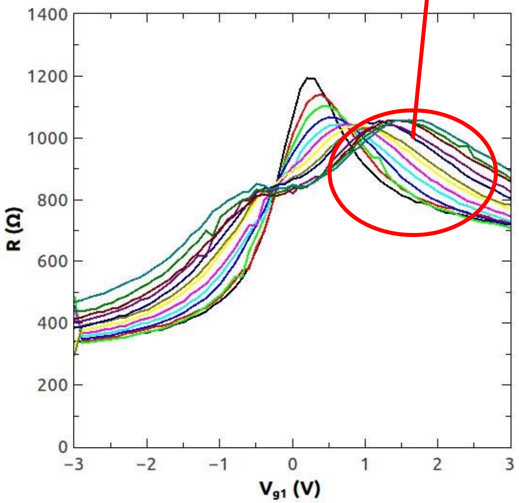


The contact gated RF transistor

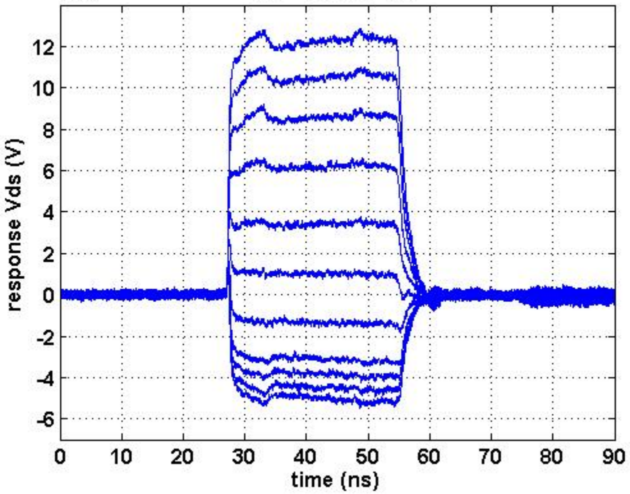




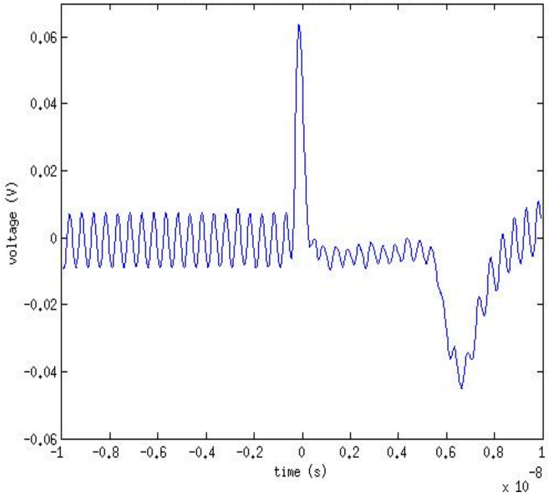
Differential resistance



Pulsed contact gating

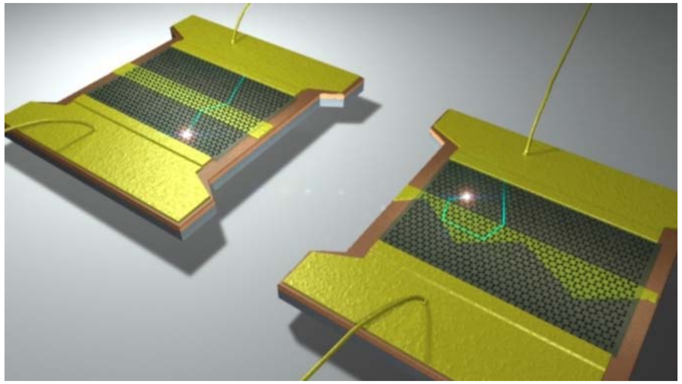


RF-gain switching



Q. Wilmart thesis

Conclusions



- Tunable p-n junctions are building blocks for Dirac Fermion Optics
- Dirac Fermion Optics proposal are still challenging but feasible
- Graphene on BN offers new perspectives for HF electronics

Thank you for your attention !